

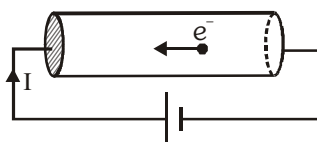
CURRENT ELECTRICITY

1. ELECTRIC CURRENT AND DRIFT VELOCITY

In previous chapters we have dealt largely with electrostatics that is, charges at rest. In this chapter we will focus on electric currents, that is, charges in motion.

1.1 Electric current

Electric charges in motion constitutes an electric current. Any medium having free electric charges is a conductor of electricity.



Positive charge flows from higher to lower potential and negative charge flows from lower to higher. Metals such as gold, silver, copper, aluminium etc. are good conductors. When charge flows in a conductor from one place to the other, then the rate of flow of charge is called electric current (I). If the moving charges are positive, the current is in the direction of motion of charge. If they are negative, the current is opposite to the direction of motion. If a charge ΔQ crosses an area in time Δt then the average electric current through the area, during this time is

$$\text{Average current } I_{av} = \frac{\Delta Q}{\Delta t}$$

- Instantaneous current $I = \lim_{\Delta t \rightarrow 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}$
- Current is a fundamental quantity with dimensions $[M^0 L^0 T^0 A^1]$
- Current is a scalar quantity with its SI unit being **ampere**. (as it doesn't obey vector laws)

Ampere : The current through any conductor is said to be one ampere if one coulomb of charge is flowing per second through any cross-section of the wire.

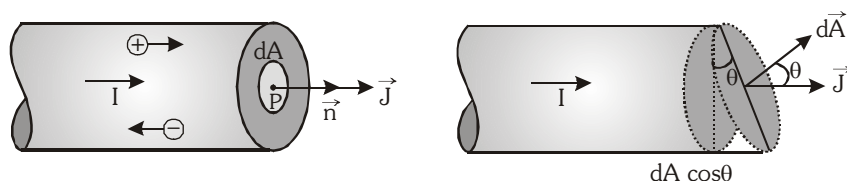
- The conventional direction of current is the direction of flow of positive charge or applied field. It is opposite to the direction of flow of negatively charged electrons or ions.



1.2 Current Density (J)

Current is a macroscopic quantity and deals with the overall rate of flow of charge through a section. To specify the current with direction in the microscopic level at a point, the term current density is introduced. Current density at any point inside a conductor is defined as a vector having magnitude equal to current per unit area surrounding that point. Remember that surface is normal to the direction of charge flow (or current passing) through that point.

- Current density at point P is given by $\vec{J} = \frac{dI}{dA} \hat{n}$



- If the area is not normal to the current, but makes an angle θ with the normal to the direction of current then $J = \frac{dI}{dA \cos \theta} \Rightarrow dI = J dA \cos \theta = \vec{J} \cdot d\vec{A} \Rightarrow I = \int \vec{J} \cdot d\vec{A}$
- Current density \vec{J} is a vector quantity. It's direction is same as that of \vec{E} . It's SI unit is ampere/m² and dimensions [L⁻²A].

1.3 Thermal speed

Conductors contain a large number of free electrons, which are in continuous random motion.

Due to random motion, the free electrons collide with positive metal ions with high frequency and undergo change in direction at each collision. So, the thermal velocities are randomly distributed in all possible directions.

Let $\vec{u}_1, \vec{u}_2, \dots, \vec{u}_N$ be the individual thermal velocities of the free electrons at any given time.

If the total number of free electrons in the conductor = N

then average velocity
$$\vec{u}_{ave} = \left[\frac{\vec{u}_1 + \vec{u}_2 + \dots + \vec{u}_N}{N} \right] = \vec{0}$$

The average thermal velocity is zero but the average thermal speed is non-zero.

1.4 Classification of Materials according to Conductivity

(i) Conductors

In some materials, the outer electrons of each atoms or molecules are loosely bound to it. These electrons are almost free to move throughout the body of the material and are called free electrons. They are also known as conduction electrons. When such a material is placed in an electric field, the free electrons move in a direction opposite to the field. Such materials are called conductors.

(ii) Insulators

Materials of another class are called insulators in which all the electrons are tightly bound to their respective atoms or molecules. Effectively, there are no free electrons. When such a material is placed in an electric field, the electrons may slightly shift opposite to the field but they cannot leave their parent atoms or molecules and hence cannot move through long distances. Such materials are also called dielectrics.

(iii) Semiconductors

Semiconductors behave like insulators at low temperatures. But at higher temperatures, a small number of electrons are able to free themselves and they respond to the applied electric field. As the number of free electrons in a semiconductor is much smaller than that in a conductor, its response is intermediary to a conductor and an insulator and hence, it is named as semiconductor. A free electron in a semiconductor leaves a vacancy in its normal bound position. These vacancies also help in conduction and are called holes.

1.5 Behaviour of conductor in absence of applied potential difference :

The free electrons present in a conductor gain energy due to the temperature of surrounding and move randomly in the conductor. The average transport and average velocity is zero for a large number of free electrons. There is no flow of current due to thermal motion of free electrons in a conductor. In the absence of applied potential difference, electrons have random motion.

The speed gained by virtue of temperature is called root mean square speed of an electron $\frac{1}{2}mv_{rms}^2 = \frac{3}{2}kT$

So root mean square speed $v_{rms} = \sqrt{\frac{3kT}{m}}$ where m is the mass of an electron, k = Boltzmann's constant

At room temperature T = 300 K, $v_{rms} = 10^5$ m/s



- **Mean free path (λ)** : The average distance travelled by an electron between two successive collisions is

the mean free path : $\lambda = \frac{\text{total distance travelled}}{\text{number of collisions}}$, ($\lambda \approx 10\text{\AA}$ in metals)

- **Relaxation time (τ)** : The average time taken by an electron between two successive collisions is the relaxation

time : $\tau = \frac{\text{total time between two collisions for all the free electrons}}{\text{number of free electrons}}$, ($\tau \approx 10^{-14}\text{s}$ in metals)

1.6 Behaviour of a conductor in the presence of applied potential difference :

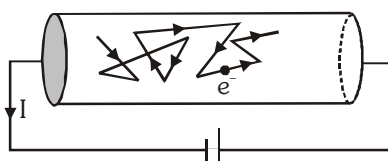
When two ends of a conductor are joined to a battery then one end is at a higher potential and the other at lower potential. This produces an electric field inside the conductor from higher to lower potential.

The field exerts an electric force on free electrons causing acceleration of each electron.

$$\text{Acceleration of electron } \vec{a} = \frac{\vec{F}}{m} = \frac{-e\vec{E}}{m}$$

1.7 Drift velocity

Drift velocity is defined as the velocity with which the free electrons get drifted towards the positive terminal under the effect of the applied external electric field. In addition to its thermal velocity, due to acceleration given by applied electric field, the electron acquires a velocity component in a direction opposite to the direction of the electric field. The gain in velocity due to the applied field is very small and is lost in the next collision.



Under the action of electric field :
Random motion of an electron
with drift superimposed on it.

At any given time, an electron has a velocity $\vec{v}_1 = \vec{u}_1 + \vec{a}\tau_1$, where \vec{u}_1 = the thermal velocity and

$\vec{a}\tau_1$ = the velocity acquired by the electron under the influence of the applied electric field.

τ_1 = the time that has elapsed since the last collision. Similarly, the velocities of the other electrons are

$$\vec{v}_2 = \vec{u}_2 + \vec{a}\tau_2, \vec{v}_3 = \vec{u}_3 + \vec{a}\tau_3, \dots, \vec{v}_N = \vec{u}_N + \vec{a}\tau_N.$$

The average velocity of all the free electrons in the conductor is equal to the drift velocity \vec{v}_d of the free electrons

$$\vec{v}_d = \frac{\vec{v}_1 + \vec{v}_2 + \vec{v}_3 + \dots + \vec{v}_N}{N} = \frac{(\vec{u}_1 + \vec{a}\tau_1) + (\vec{u}_2 + \vec{a}\tau_2) + \dots + (\vec{u}_N + \vec{a}\tau_N)}{N} = \frac{(\vec{u}_1 + \vec{u}_2 + \dots + \vec{u}_N)}{N} + \vec{a} \left(\frac{\tau_1 + \tau_2 + \dots + \tau_N}{N} \right)$$

$$\therefore \frac{\vec{u}_1 + \vec{u}_2 + \dots + \vec{u}_N}{N} = \vec{0} \therefore \vec{v}_d = \vec{a} \left(\frac{\tau_1 + \tau_2 + \dots + \tau_N}{N} \right) \Rightarrow \vec{v}_d = \vec{a}\tau = -\frac{e\vec{E}}{m}\tau$$

Note : Order of drift velocity is 10^{-4} m/s.



1.8 Relation between Current and Drift velocity :

Let n = number density of free electrons and A = area of cross-section of the conductor.

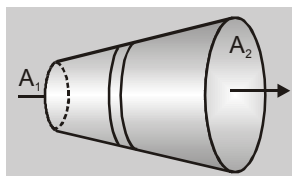
Number of free electrons in the conductor of length $L = nAL$, Total charge on these free electrons $\Delta q = neAL$

Time taken by drifting electrons to cross the conductor $\Delta t = \frac{L}{v_d}$ \therefore current $I = \frac{\Delta q}{\Delta t} = neAL \left(\frac{v_d}{L} \right) = neAv_d$

$$I = neAv_d$$

GOLDEN KEY POINTS

- The conductor remains uncharged when current flows through it because the charge entering at one end per second is equal to charge leaving the other end per second.
- For a given conductor current does not change with change in its cross-section because current is simply the rate of flow of charge. If a steady current flows in a metallic conductor of non uniform cross section :
 - I is same along the wire .
 - Current density, electric field strength, drift velocity are inversely proportional to area. Here $I_1 = I_2$ but $A_1 < A_2$ so $J_1 > J_2$, $E_1 > E_2$, $v_{d1} > v_{d2}$



- If n particles each having a charge q pass per second per unit area then current associated with cross-sectional area A is $I = \frac{\Delta q}{\Delta t} = nqA$.
- If there are n particles per unit volume each having a charge q and moving with velocity v then current through cross-sectional area A is $I = \frac{\Delta q}{\Delta t} = nqvA$
- If a charge q is moving in a circle of radius r with speed v then its time period is $T = 2\pi r/v$. The equivalent current $I = \frac{q}{T} = \frac{qv}{2\pi r}$.
- Order of free e^- density in conductors = 10^{28} electrons/ m^3 , while in semiconductors = 10^{16} e^-/m^3
- Electric field outside a current carrying conductor is zero but inside a conductor it is $\frac{V}{\ell}$.

Terms	Thermal speed	Mean free path	Relaxation time	Drift speed
	v_T	λ	τ	v_d
Order of magnitude	10^5 m/s	10 \AA	10^{-14} s	10^{-4} m/s



System	Current carriers
A bar made of silver or any metal	Free electrons
Hydrogen discharge tube	Electrons and (+ve) Ions
Voltaic cell	H^+ and SO_4^{-2} (Ions)
Lead Accumulator	H^+ , SO_4^{-2} Ions
Semiconductor	Electrons and holes
Super conductor	Electrons

- If the temperature of a conductor increases, the amplitude of vibrations of positive ions in the conductor also increase. Consequently the free electrons collide more frequently with the vibrating ions and as a result, the average relaxation time decreases.
- Mean free path of conduction electrons = Drift velocity \times Relaxation time

Illustrations

Illustration 1.

What will be the number of electrons passing through a heater wire in one minute, if it carries a current of 8 A?

Solution

$$I = \frac{ne}{t} \Rightarrow n = \frac{It}{e} = \frac{8 \times 60}{1.6 \times 10^{-19}} = 3 \times 10^{21} \text{ electrons.}$$

Illustration 2.

The current through a wire depends on time as $i = (2 + 3t)$ A. Calculate the charge crossed through a cross section of the wire in first 10 seconds.

Solution

$$i = \frac{dq}{dt} \Rightarrow dq = (2 + 3t)dt$$

$$\int_0^q dq = \int_0^{10} (2 + 3t)dt \Rightarrow q = \left(2t + \frac{3t^2}{2} \right)_0^{10} = 2 \times 10 + \frac{3}{2} \times 100 = 20 + 150 = 170 \text{ C.}$$

Illustration 3.

Current through a wire decreases linearly from 4 A to zero in 10 s. Calculate the charge flown through the wire during this interval of time.

Solution

Charge flown = average current \times time

$$= \left[\frac{4 + 0}{2} \right] \times 10 = 20 \text{ C}$$

Illustration 4.

The current density at a point is $\vec{J} = (2 \times 10^4 \hat{j}) \text{ Am}^{-2}$.

Find the rate of charge flow through a cross sectional area $\vec{S} = (2\hat{i} + 3\hat{j}) \text{ cm}^2$

Solution

The rate of flow of charge = current = $I = \int \vec{J} \cdot d\vec{S} \Rightarrow I = \vec{J} \cdot \vec{S} = (2 \times 10^4) [\hat{j} \cdot (2\hat{i} + 3\hat{j})] \times 10^{-4} \text{ A} = 6 \text{ A}.$



Illustration 5.

Find the number of free electrons per unit volume of a metallic wire of density 10^4 kg/m^3 , atomic mass number 100 if the number of free electrons per atom is one.

Solution

$$\text{Number of free charge particles per unit volume (n)} = \frac{\text{total free charge particles}}{\text{total volume}}$$

\therefore Number of free electron per atom is one implies that total free electrons = total number of atoms = $\frac{N_A}{M_w} \times M$

$$\text{So } n = \frac{\frac{N_A}{M_w} \times M}{V} = \frac{N_A}{M_w} \times d = \frac{6.023 \times 10^{23} \times 10^4}{100 \times 10^{-3}} = 6.023 \times 10^{28}.$$

BEGINNER'S BOX-1

- 10,000 alpha particles pass per minute through a straight tube of radius r . What is the resulting electric current?
- The potential difference applied to an X-ray tube is 5 kV and the current through it is 3.2 mA. What is the number of electrons striking the target per second?
- The diameter of a copper wire is 2 mm, a steady current of 6.25 A is generated by $8.5 \times 10^{28}/\text{m}^3$ electrons flowing through it. Calculate the drift velocity of conduction electrons.
- A silver wire of 1mm diameter has a charge of 90 coulombs flowing in 1 hours and 15 minutes. Silver contains 5.8×10^{28} free electrons per cm^3 . Find the current in the wire and drift velocity of the electrons.

2. OHM'S LAW AND ELECTRIC RESISTANCE

2.1 Relation between Current density, Conductivity and Electric field

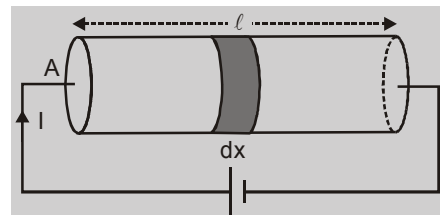
Let the number of free electrons per unit volume in a conductor = n

Cross sectional area = A

Total number of electrons in dx length = $n (A dx)$

Total charge $dQ = n (A dx)e$

Current $I = \frac{dQ}{dt} = nAe \frac{dx}{dt} \Rightarrow I = neAv_d$



Current density $J = \frac{I}{A} = nev_d \Rightarrow J = ne \left(\frac{eE}{m} \right) \tau \quad \therefore v_d = \left(\frac{eE}{m} \right) \tau$

$$J = \left(\frac{ne^2 \tau}{m} \right) E \Rightarrow J = \sigma E, \text{ where Conductivity } \sigma = \frac{ne^2 \tau}{m}$$

In vector form $\vec{J} = \sigma \vec{E}$ (This is Ohm's law at microscopic level)

σ depends only on the material of the conductor and its temperature.



2.2 Ohm's law

$$J = \sigma E$$

ℓ = length of conductor

$$\frac{I}{A} = \sigma \frac{V}{\ell}$$

V = Voltage applied across conductor

$$\frac{I}{A} = \frac{V}{\rho \ell}$$

$$\sigma = \frac{1}{\rho}$$

$$V = \left(\frac{\rho \ell}{A} \right) I$$

ρ = Resistivity or specific resistance of material

$$V = RI$$

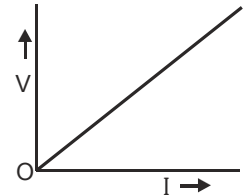
$$R = \frac{\rho \ell}{A}$$

R is constant known as the resistance of the wire whose unit is ohm (Ω).

2.3. V-I Characteristics

(A) Linear V-I characteristics

At constant temperature, current is directly proportional to the applied potential difference. This law is called ohm's law and substances which obey it are called ohmic or linear conductors.



(B) Non- Linear V-I characteristics

- The relation between V and I depends on the sign of V . In other words, if I is the current for a certain V , then reversing the direction of V keeping its magnitude fixed, does not produce a current of the same magnitude as I in the opposite direction (Figure 1).

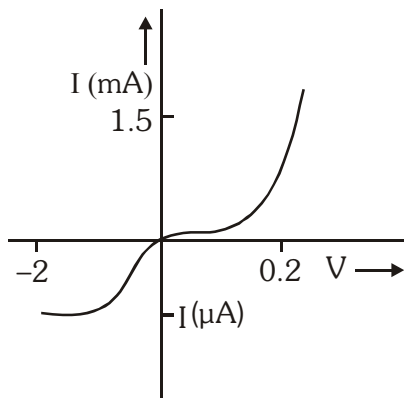


FIGURE 1 : Characteristic curve of a diode, Note the different scales for negative and positive values of the voltage and current

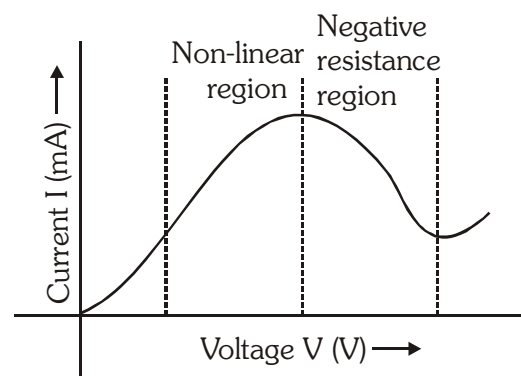


FIGURE 2 : Variation of current versus voltage for GaAs.

- The relation between V and I is not unique, i.e., there is more than one value of V for the same current I (Figure 2). A material exhibiting such a behaviour is GaAs.



2.4 Resistance

The resistance of a conductor is the opposition to the flow of charge which the conductor offers. When a potential difference is applied across a conductor, free electrons get accelerated and collide with positive ions and their motion is thus opposed. This opposition offered by the ions is called the resistance of the conductor.

Unit : ohm, volt/ampere,

Dimensions = $[M L^2 T^{-3} A^{-2}]$

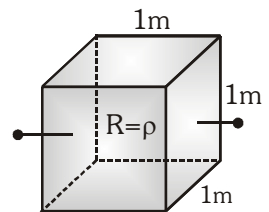
Resistance depends on :

- Length of the conductor $R \propto \ell$
- Area of cross-section of the conductor $R \propto \frac{1}{A}$
- Nature of material of the conductor $R = \frac{\rho \ell}{A}$

2.5 Resistivity and conductivity

Resistivity : $\rho = RA/\ell$ if $\ell = 1$ units, $A = 1$ units then $\rho = R$ units

The specific resistance of a material is equal to the resistance of a wire of that material with unit cross sectional area and unit length.



Conductivity is the inverse of resistivity $\sigma = \frac{1}{\rho}$

Resistivity depends on

- (i) Nature of material (ii) Temperature of material

Resistivity does not depend on the size and shape of the material because it is a characteristic property of the conducting material.

2.6 Mobility

As we have seen, conductivity arises as a result of mobile charge carriers. In metals, these mobile charge carriers are electrons; in an ionised gas, they are electrons and positively charged ions; in an electrolyte, these can be both positive and negative ions.

An important quantity is the mobility μ defined as the magnitude of the drift velocity per unit electric field :

$$\mu = \frac{|v_d|}{E}$$

The SI unit of mobility is $m^2/V-s$ and is 10^4 times the mobility in practical units ($cm^2/V-s$). Mobility is positive.

$$v_d = \frac{e \tau E}{m} \quad \mu = \frac{v_d}{E} = \frac{e \tau}{m}$$

where τ is the relaxation time for electrons.



2.7 Temperature dependence of resistivity and resistance

The resistivity of a material is found to be dependent on the temperature over a limited range of temperatures (not too large). The resistivity of a metallic conductor is approximately given by

$$\rho_T = \rho_0[1 + \alpha(T - T_0)]$$

Where ρ_T is the resistivity at a temperature T and ρ_0 is the resistivity at a reference temperature T_0 . Here, α is called the temperature co-efficient of resistivity.

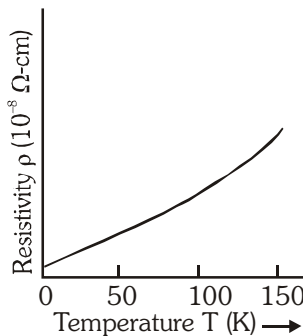


Figure
Resistivity ρ_T of copper as a function of temperature T .

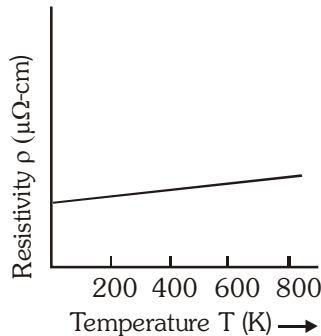


Figure Resistivity ρ_T of nichrome as a function of absolute temperature T .

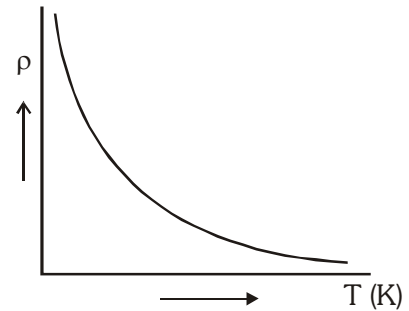


Figure
Temperature dependence of resistivity for a typical semiconductor

- Unit of α is $\frac{1}{^\circ\text{C}}$
- Resistance corresponding to temperature difference (ΔT) is given as $R_t = R_0(1 + \alpha\Delta T)$
Where R_t = Resistance at $t^\circ\text{C}$, R_0 = Resistance at 0°C
 ΔT = Change in temperature, α = Temperature coefficient of resistance
*[For metals : α is positive but for semiconductors and insulators : α is negative]
- Resistance of the conductor decreases linearly with decrease in temperature and becomes zero at a specific temperature. This temperature is called critical temperature. Below this temperature a conductor becomes a superconductor.

2.8 Colour coding of carbon resistor (For self study)

Resistors in the higher range are made mostly from carbon. Carbon resistors are compact, inexpensive and thus find extensive use in electronic circuits. Carbon resistors are small in size and hence their values are given using a colour code.

TABLE : RESISTOR COLOUR CODES

Colour	Number	Multiplier	Tolerance (%)
Black	0	1	
Brown	1	10^1	
Red	2	10^2	
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	
Blue	6	10^6	
Violet	7	10^7	
Gray	8	10^8	
White	9	10^9	
Gold			5
Silver			10
No colour			20



- Here is a mnemonic to memorise the names of colours in a sequence.

BBROY of Great Britain had a Very Good Wife

The resistors have a set of co-axial coloured rings on them whose significance are listed in Table. The first two bands from the end indicate the first two significant figures of the resistance in ohms. The third band indicates the decimal multiplier (as listed in Table). The last band stands for tolerance or possible variation in percentage about the indicated values. Sometimes, this last band is absent and that indicates a tolerance of 20%. For example, if the four colours are orange, blue, yellow and gold, the resistance value is $36 \times 10^4 \Omega$, with a tolerance value of 5%.

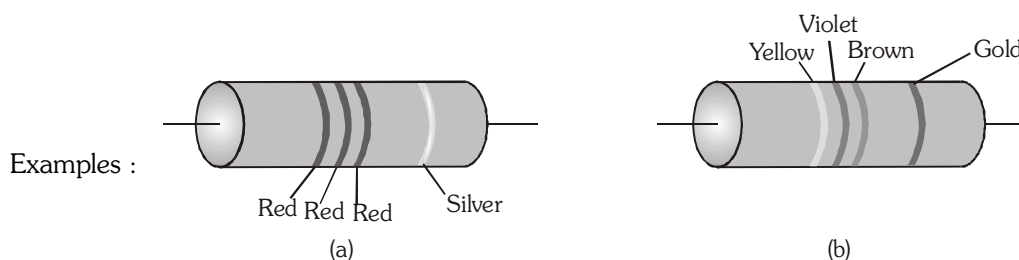
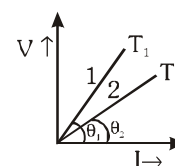


Figure : Colour coded resistors **(a)** $(22 \times 10^2 \Omega) \pm 10 \%$, **(b)** $(47 \times 10 \Omega) \pm 5 \%$

GOLDEN KEY POINTS

- If a wire is stretched to n times of its original length, its new resistance will be n^2 times.
- If a wire is stretched such that its radius is reduced to $\frac{1}{n}$ th of its original value, then its new resistance will increase to n^4 times; similarly resistance will decrease to n^4 times if radius is increased to n times by contraction.
- $x \%$ change is brought in length of a wire, its resistance will change by $2x \%$. (if change is very small)
- Ohm's law is not a fundamental law of nature. As it is possible that for an element :-
 - (i) V depends on I nonlinearly (e.g. vacuum tubes)
 - (ii) Relation between V and I depends on the sign of V for the same value [forward and reverse bias in diode]
 - (iii) The relation between V and I is not unique. That is for the same value of I there is more than one value of V .
- In general :
 - (i) $\rho_{\text{alloy}} > \rho_{\text{semiconductor}} > \rho_{\text{conductor}}$
 - (ii) Temperature coefficients of alloys are lower than pure metals.
 - (iii) Resistance of most of non metals decrease with increase in temperature. (e.g. carbon)
 - (iv) The resistivity of an insulator (e.g. amber) is greater than a metal by a factor of 10^{22} .
- Temperature coefficient (α) of semi conductor including carbon (graphite), insulator and electrolytes is negative.
- At different temperatures V - I curves are different.

Here $\tan \theta_1 > \tan \theta_2$ So $R_1 > R_2$ i.e. $T_1 > T_2$

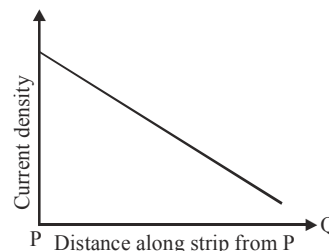


- The **heating element** devices like heater, geyser, electric iron (usual known as press) etc are made of **nichrome** because it has high resistivity and high melting point. It does not react with air and acquires steady state when red hot at 800°C .
- **Fuse wire** is made of **tin lead alloy** because it has low melting point and high resistivity. The fuse is used in series, and melts to result in an open circuit when current exceeds the safety limit.
- **Resistances** of resistance box are made of **manganin** or **constantan** because they have moderate resistivity and very small temperature coefficient of resistance. The resistivity is nearly independent of temperature.
- The **filament of bulb** is made up of **tungsten** because it has low resistivity, high melting point of 3300 K and emits light at 2400 K . The bulb is filled with inert gas because at high temperatures tungsten reacts with air forming oxide.
- The **connection wires** are made of **copper** because it has low resistivity.

Illustrations

Illustration 6.

An electric current flows along an insulated strip PQ of a metallic conductor. The current density in the strip varies as shown in the graph. Which one of the following statements could explain this variation?



- (A) The strip is narrower at P than at Q
- (B) The strip is narrower at Q than at P
- (C) The potential gradient along the strip is uniform
- (D) The resistance per unit length of the strip is constant.

Ans. (A)

Solution

The current density at P is higher than at Q. For the same current flowing through the metallic conductor PQ, the cross-sectional area at P is narrower than at Q. The resistance per unit length r is given by $r = \frac{\rho}{A}$ where ρ is the resistivity and A is the cross-sectional area of the conductor PQ. Thus, r is inversely proportional to the cross-sectional area A of the conductor.

Illustration 7.

A constant voltage is applied across a wire of constant length. How does the drift velocity of electrons depends on the area of cross-section of wire.

Solution

$$v_d = \mu E, \quad \mu = \text{mobility of free electrons} = \frac{e\tau}{m} \quad \text{and} \quad E = \text{electric field} = \frac{V}{L}$$

$$\text{so } v_d = \mu \frac{V}{L} ; \text{ here } \mu \text{ is constant.}$$

If V and L are constant then v_d does not depend on area.

Illustration 8.

Draw the colour code for $42\text{ k}\Omega \pm 10\%$ carbon resistance.

Solution

According to colour code, colour for digit 4 is yellow, for digit 2 it is red, for digit 3 the colour is orange and 10% tolerance is represented by silver colour. So colour code should be yellow, red, orange and silver.



Illustration 9.

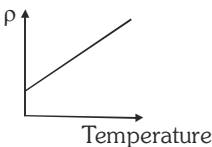
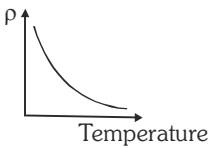
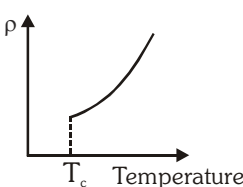
At room temperature (0°C) the resistance of a heating element is $100\ \Omega$. Calculate the temperature of the element if the resistance is found to be $117\ \Omega$ (the temperature coefficient of resistance of the material is $1.7 \times 10^{-4}\ ^\circ\text{C}^{-1}$)

Solution

$$\begin{aligned} \therefore R_\theta &= R_0 (1 + \alpha\theta) \therefore 117 = 100(1 + \alpha\theta) \\ \Rightarrow \theta &= \frac{117-100}{100\alpha} = \frac{17}{100 \times 1.7 \times 10^{-4}} = 1000^\circ\text{C} \end{aligned}$$

BEGINNER'S BOX-2

1. The dimensions of a block is $100\text{ m} \times 1\text{ m} \times 1\text{ m}$. The specific resistance of the material of the block is $4 \times 10^{-6}\ \Omega\text{-m}$. Calculate its resistance across its square faces.
2. If a copper wire is stretched to make its cross-sectional radius 0.1% thinner, then what is the percentage increase in its resistance ?
3. A wire of resistance $5\ \Omega$ is drawn out so that its length is increased to twice its original length. Calculate its new resistance and resistivity.
4. At what temperature, would the resistance of a copper wire be double its resistance at 0°C ? If $\alpha = \frac{1}{273}\ ^\circ\text{C}^{-1}$.
5. Match the following items –

graph	solid
(A) 	(p) Semiconductor
(B) 	(q) Conductor
(C) 	(r) Conductor which exhibits super conductivity



6. Match the column I with column II -

Column I	Column II
(A) Filament of electric bulb	(p) tin-lead alloy
(B) Fuse wire	(q) Manganin
(C) Resistance of resistance box	(r) Nichrome
(D) Filament of heating devices (heater, geyser, press etc)	(s) Tungsten
	(t) Constantan

3. COMBINATION OF RESISTORS AND KIRCHHOFF'S LAW

3.1 Combination of resistors

• Series Combination

- Same current passes through each resistance
- Voltage across each resistance is directly proportional to the value of resistance

$$V_1 = iR_1, V_2 = iR_2, V_3 = iR_3,$$

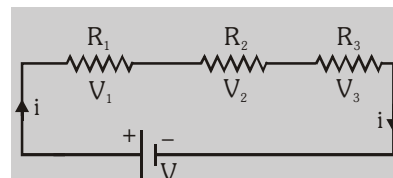
- Sum of the voltages across all resistances is equal to the voltage applied across the circuit.

$$\text{i.e., } V = V_1 + V_2 + V_3$$

$$\text{or } iR = iR_1 + iR_2 + iR_3$$

$$\text{or } R = R_1 + R_2 + R_3$$

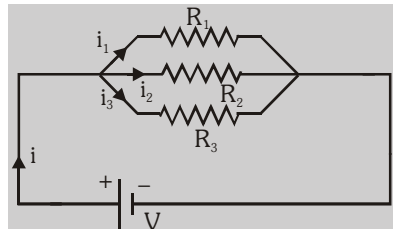
Where R = equivalent resistance



• Parallel Combination

- There is same potential drop across each resistance.
- Current in each resistance is inversely proportional to the value of resistance.

$$i_1 = \frac{V}{R_1}, i_2 = \frac{V}{R_2}, i_3 = \frac{V}{R_3}$$



- Current flowing in the circuit is the sum of the currents in the individual resistance.

$$i = i_1 + i_2 + i_3$$

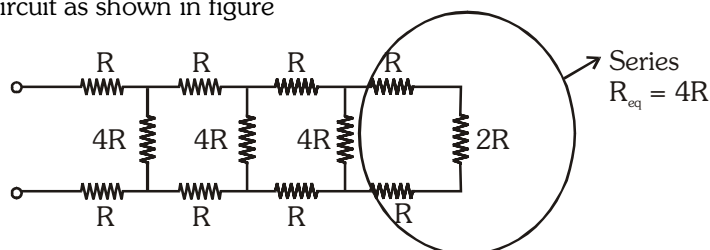
$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \Rightarrow \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

• Mixed grouping :

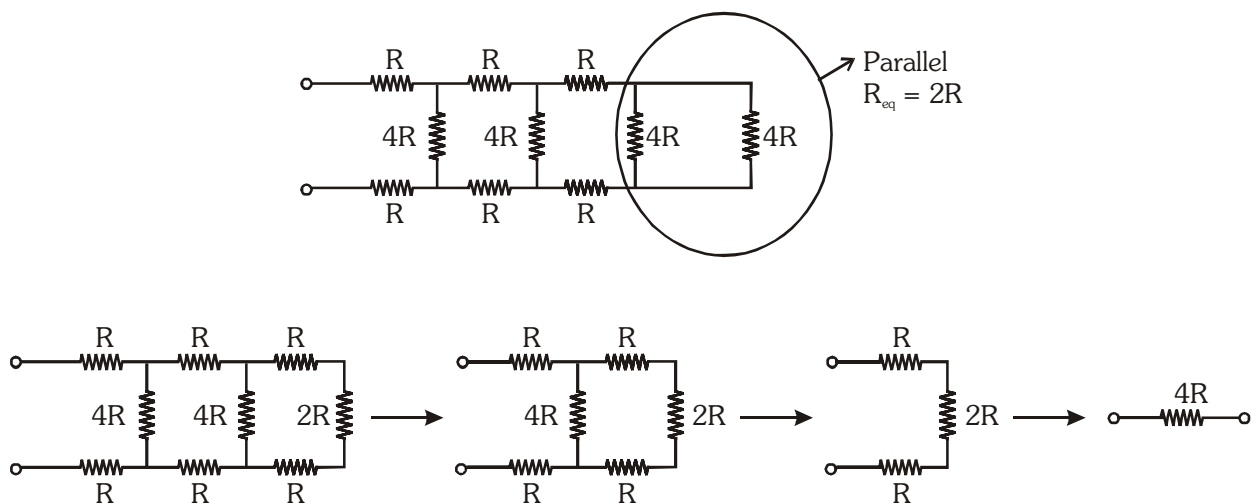
When a group of resistors is neither combined in parallel nor in series grouping, the combination is called as mixed grouping. The equivalent resistance corresponding to mixed grouping can be found by one of the following methods:

Method of successive reduction : This method is based on simplification of circuit by successive reduction of series and parallel combinations.

For eg., Let us take a circuit as shown in figure



The circuit can be reduced to

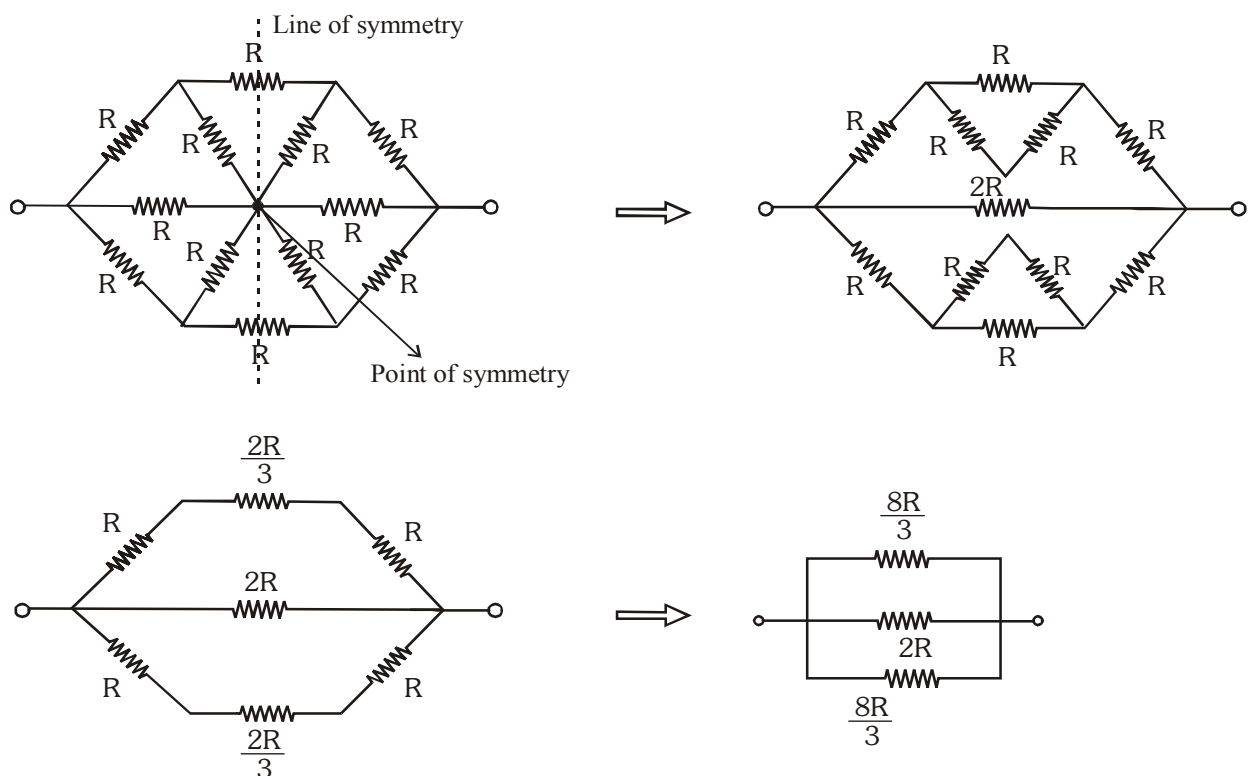


Method of symmetry :

A line drawn across the circuit perpendicular to the line joining the two points between which resistance is to be found, which divides a circuit in two mirror images is a line of symmetry. This line is an equipotential line. By removing a resistor on equipotential line or by placing a conductor on this circuit is modified without altering its electrical properties. Now the modified circuit is solved by method of successive reduction.

A point of symmetry is a false junction. Current does not get redistributed at this point. By separating the elements carrying the same current, the circuit is made simple & is then solved by method of successive reduction.

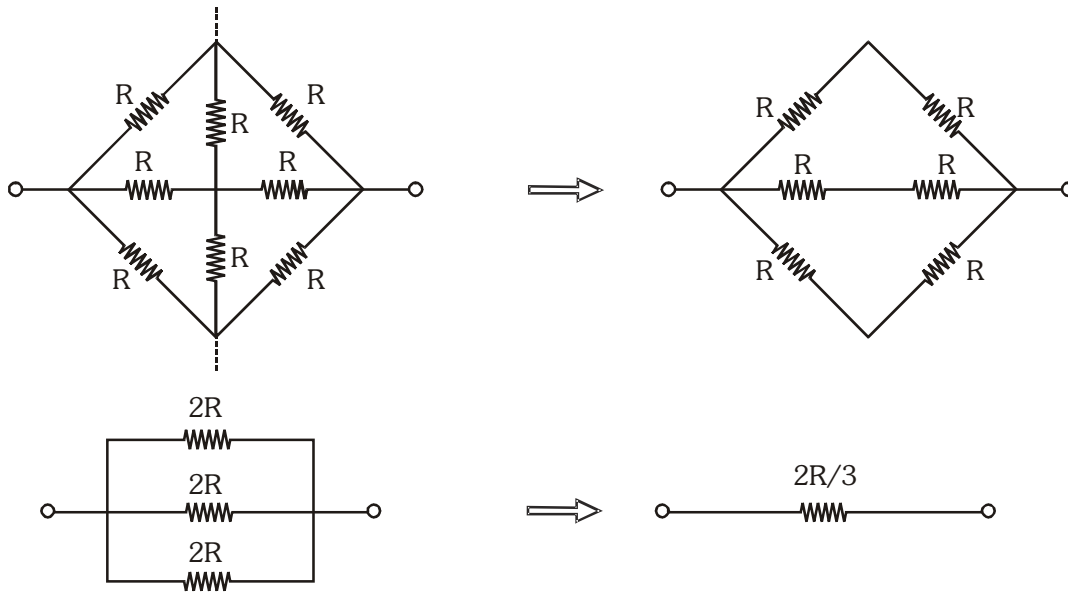
Example 1.



$$\frac{1}{R_{eq}} = \frac{3}{8R} + \frac{1}{2R} + \frac{3}{8R} \Rightarrow R_{eq} = \frac{4R}{5}$$



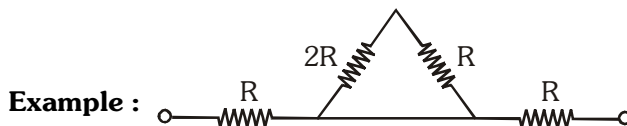
Example 2.



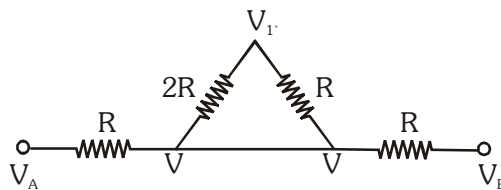
Nodal method (For short-circuits)

When two points are connected with a conducting wire (having zero resistance), the potential difference across the wire becomes zero i.e. the two nodes will have same potential. To calculate the equivalent resistance, following steps are taken

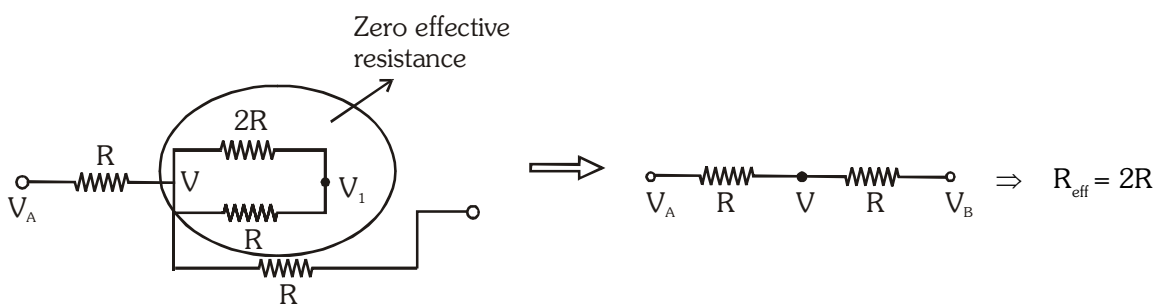
1. Identify the nodes with same potential.
2. Allot the potential on every node.
3. Redraw the circuit and calculate the equivalent resistance.



The circuit can be solved as



The circuit can be redrawn as



3.2 Kirchhoff's Law

There are two laws given by Kirchhoff for determination of potential difference and current in different branches of any complicated network.

- First law or Junction law**

In an electric circuit, the algebraic sum of the currents meeting at any junction in the circuit is zero.

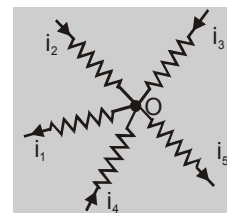
or

Sum of the currents entering the junction is equal to sum of the currents leaving the junction.

$$\sum i = 0$$

Law of conservation of charge is the basis behind of continuity equation

$$i_1 - i_2 - i_3 - i_4 + i_5 = 0 \Rightarrow i_1 + i_5 = i_2 + i_3 + i_4$$



This is based on law of conservation of charge.

- Second law or Loop law**

In any closed circuit the algebraic sum of e.m.f.'s and algebraic sum of potential drops is zero.

$$\sum IR + \sum E = 0$$

while moving from negative to positive terminal inside a cell, e.m.f. is taken positive while moving in the direction of current in a circuit the potential drop (i.e. IR) across a resistance is taken negative.

- This law is based on law of conservation of energy.**

Kirchhoff's method : Working rule is described below :

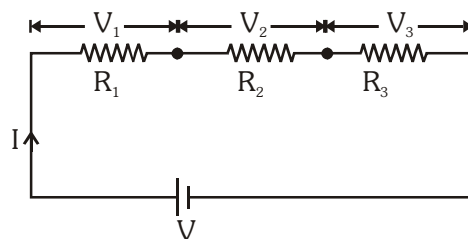
- Assume same current to be entering & leaving the circuit.
- Distribute currents and find relationship between them using second law.
- Find voltage across the circuit
- $R_{eq} = \frac{\text{Voltage across the circuit}}{\text{Current through the circuit}}$

GOLDEN KEY POINTS

- If n resistance (each R) are connected in series their effective resistance will be nR .
- If n resistances (each R) are connected in parallel then their effective resistance will be $\frac{R}{n}$.
- The equivalent resistance of parallel combination is lower than the value of the lowest resistance in the combination.
- When resistors are connected in series in a battery circuit then the ratio of potential differences across the resistors is equal to ratio of their respective resistances.

$$V_1 : V_2 : V_3 = R_1 : R_2 : R_3$$

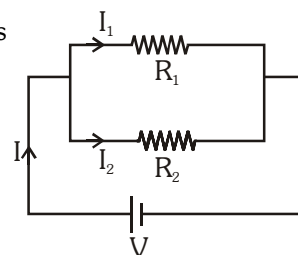
$$V_1 = \frac{R_1}{R_1 + R_2 + R_3} V; V_2 = \frac{R_2}{R_1 + R_2 + R_3} V; V_3 = \frac{R_3}{R_1 + R_2 + R_3} V$$



- When resistors are connected in parallel in a battery circuit then the ratio of currents through them will be the ratio of reciprocals of their respective resistances.

$$I_1 : I_2 :: \frac{1}{R_1} : \frac{1}{R_2} = R_2 : R_1$$

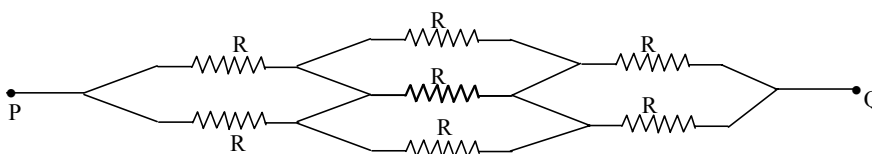
$$I_1 = \frac{R_2}{R_1 + R_2} I; \quad I_2 = \frac{R_1}{R_1 + R_2} I$$



Illustrations

Illustration 10.

Equivalent resistance for the given figure between P and Q is $NR/3$. Find the value of N.



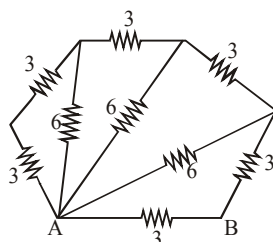
Solution

$$\frac{R}{2} \quad \frac{R}{3} \quad \frac{R}{2} \quad R_{\text{net}} = \frac{4R}{3} \Rightarrow N = 4$$

Ans. 4

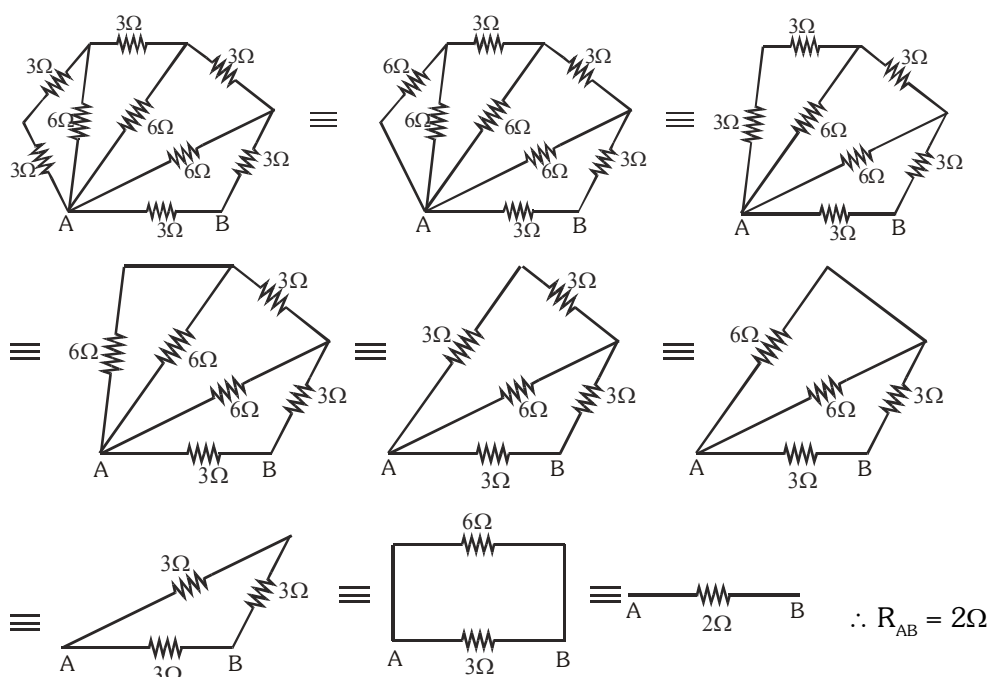
Illustration 11.

All resistances in the diagram below are in ohms. Find the effective resistance between the points A and B (in Ω).



Solution

The given system can be reduced as shown in figure.

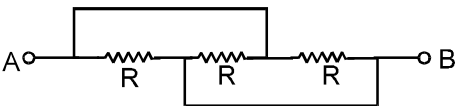


Ans. 2

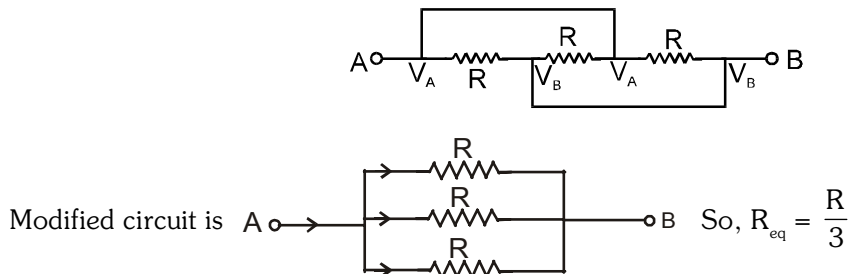


Illustration 12.

Find the equivalent resistance between A and B


Solution

Here all the resistances are connected between the terminals A and B



$$\text{So, } R_{eq} = \frac{R}{3}$$

Illustration 13.

Resistances $R, 2R, 4R, 8R, \dots, \infty$ are connected in parallel. What is their resultant resistance?

Solution

$$\frac{1}{R_{eq}} = \frac{1}{R} + \frac{1}{2R} + \frac{1}{4R} + \frac{1}{8R} + \dots = \frac{1}{R} \left[1 + \frac{1}{2} + \frac{1}{4} + \dots \right] = \frac{1}{R} \left[\frac{1}{1 - \frac{1}{2}} \right] = \frac{2}{R} \Rightarrow R_{eq} = \frac{R}{2}$$

Illustration 14.

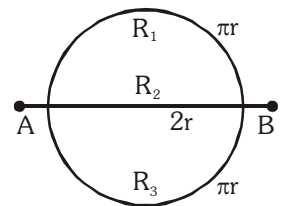
A wire of $\rho_L = 10^{-6} \Omega/\text{m}$ is turned in the form of a circle of diameter 2 m. A piece of same material is connected as a diameter AB. Then find the resistance between A and B.

Solution

$$\because R = \rho_L \times \text{length}$$

$$\therefore R_1 = \pi \times 10^{-6} \Omega, R_2 = 2 \times 10^{-6} \Omega, R_3 = \pi \times 10^{-6} \Omega$$

$$\frac{1}{R_{AB}} = \frac{1}{\pi \times 10^{-6}} + \frac{1}{2 \times 10^{-6}} + \frac{1}{\pi \times 10^{-6}} ; R_{AB} = 0.88 \times 10^{-6} \text{ ohm.}$$

**Illustration 15.**

Give the nature of V-I graph for

(a) ohmic (b) non-ohmic

circuit elements. Give one example of each type.

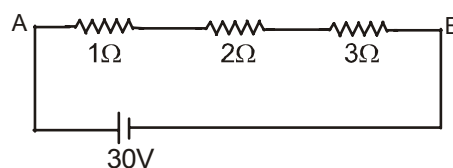
Solution

Linear graph for ohmic. Non-linear graph for non-ohmic circuit elements.

eg : Ohmic – electrical resistance, Non ohmic – diode.

Illustration 16.

Find the current in the circuit

**Solution**

$$R_{eq} = 1 + 2 + 3 = 6 \Omega \text{ the given circuit is equivalent to}$$

$$\text{current } i = \frac{V}{R_{eq}} = \frac{30}{6} = 5A$$

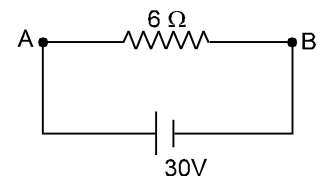
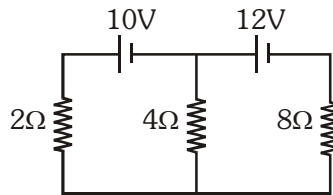


Illustration 17.

For the electric circuit shown here, write the Kirchhoff's circuital law equations, the solutions of which will give currents in the three resistors. Do not solve the equations. [AIPMT (Mains) 2006]



Solution

$$\begin{aligned} i_1 &= i_2 + i_3 \\ 2i_1 - 10 + 4i_3 &= 0 \\ 8i_2 - 12 - 4i_3 &= 0 \end{aligned}$$

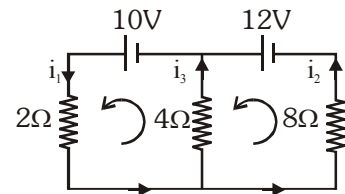
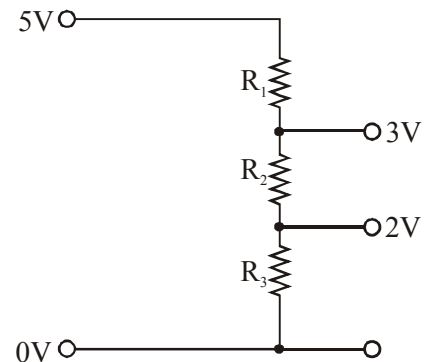


Illustration 18.

A potential divider is used to give outputs of 2 V and 3 V from a 5 V source, as shown in figure. Which combination of resistances, R_1 , R_2 and R_3 gives the correct voltages?



R_1	R_2	R_3
(A) 1 kΩ	1 kΩ	2 kΩ
(B) 2 kΩ	1 kΩ	2 kΩ
(C) 3 kΩ	2 kΩ	2 kΩ
(D) 3 kΩ	2 kΩ	3 kΩ

Solution

Ans. (B)

For resistors in series connection, current (I) is the same through the resistors. In other words, ratio of the voltage drop across each resistor with its resistance is the same.

$$\text{That is } I = \frac{5-3}{R_1} = \frac{3-2}{R_2} = \frac{2}{R_3} \text{ i.e., } R_1 : R_2 : R_3 = 2 : 1 : 2.$$

Illustration 19.

In the given circuit, find the current (in mA) in the wire between points A and B.

Solution

A & B are short circuited

$$\text{So } R_{\text{eff}} = \frac{4}{3} \text{ k}\Omega$$

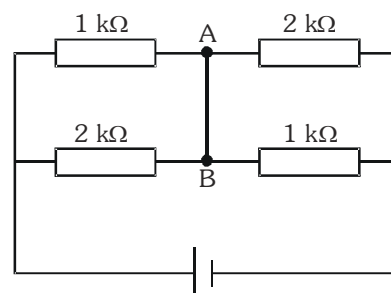
$$I_T = \frac{32}{4/3 \text{ k}\Omega} = 24 \text{ mA}$$

$$\frac{I_1}{I_2} = \frac{R_2}{R_1} = \frac{2}{1}$$

$$\Rightarrow I_1 = \frac{2}{3} \times 24 = 16 \text{ mA} \Rightarrow I_2 = \frac{1}{3} \times 24 = 8 \text{ mA}$$

The required current is

$$\begin{aligned} &= I_1 - I_2 \\ &= 16 - 8 = 8 \text{ mA} \end{aligned}$$



Ans. 8

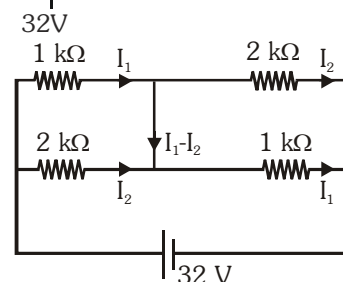
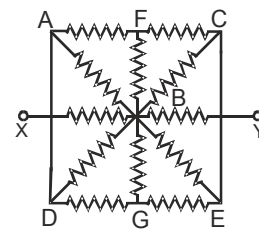


Illustration 20.

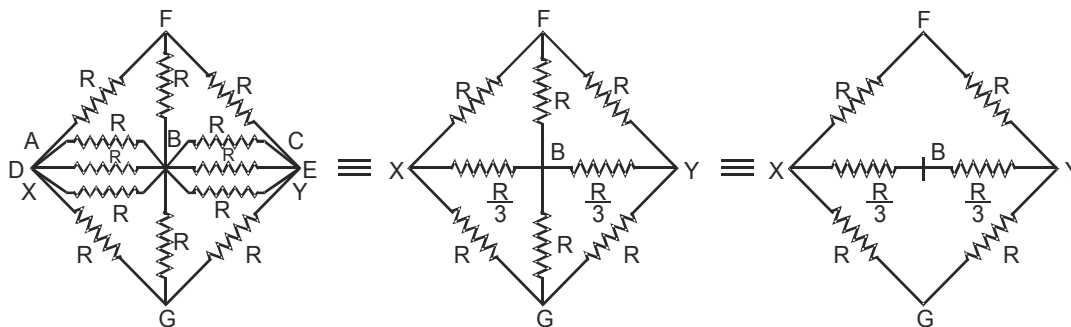
Twelve identical resistances each of resistance R are connected as in figure.

Find the net resistance between X and Y .



Solution

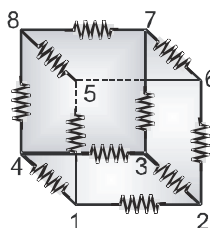
Given circuit can be modified according to following figures :



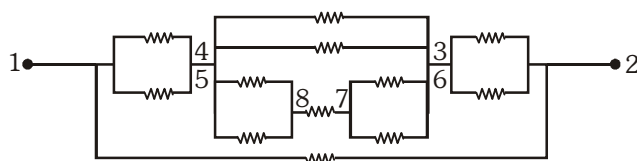
$$\frac{1}{R_{xy}} = \frac{1}{2R} + \frac{3}{2R} + \frac{1}{2R} = \frac{5}{2R} \Rightarrow R_{xy} = \frac{2R}{5}$$

Illustration 21.

A frame of cube is made by wires each of resistance r then prove that -



- (a) Resistance between two nearer corners $R_{12} = \frac{7}{12}r$
- (b) Resistance across face diagonal $R_{13} = \frac{3}{4}r$
- (c) Resistance across main diagonal $R_{17} = \frac{5}{6}r$
- (a) Resistance between two nearer corners

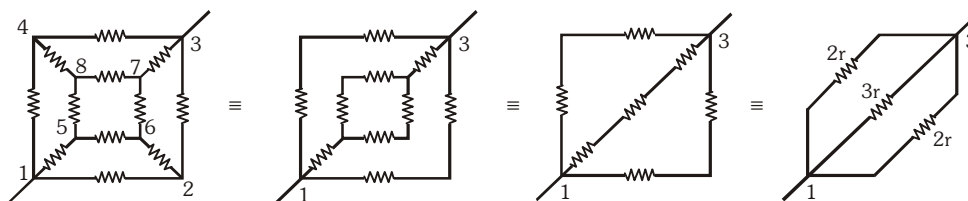


Equivalent resistance between 1 and 2 $\Rightarrow R_{12} = \frac{7}{12}r$



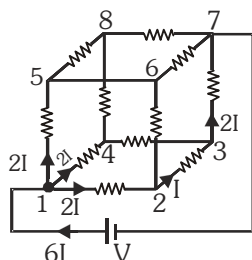
- (b) Resistance across face diagonal

Given circuit can be drawn as



Equivalent resistance between 1 and 3 $\Rightarrow R_{13} = \frac{3}{4}r$

- (c) Resistance across main diagonal

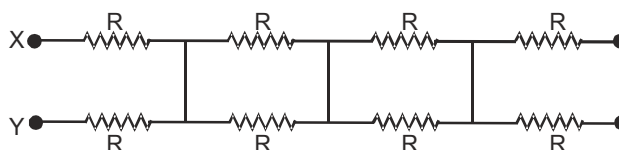


In loop 12371, applying KVL : $V = 2Ir + Ir + 2Ir = 5Ir$ So

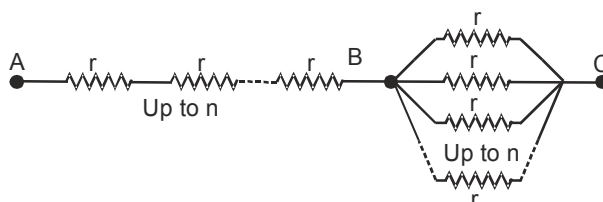
$$R_{17} = \frac{V}{6I} = \frac{5r}{6}$$

BEGINNER'S BOX-3

1. For following circuit, what is the value of total resistance between X and Y ?



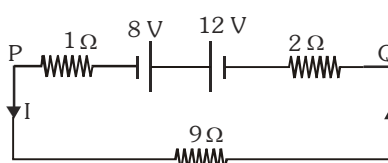
2. In the following figure what is the resultant resistance between A and C ?



3. What is the smallest resistance that can be obtained by ten $\frac{1}{10} \Omega$ resistors ?
4. Two wires of the same metal have the same length, but their cross sectional areas are in the ratio 3 : 1. They are joined in series. The resistance of the thicker wire is 10Ω . Then what will be the total resistance of the combination ?
5. What is the value of current I in the following circuit ?



6. In the given circuit, calculate the potential difference between the points P and Q.



4. CELLS, COMBINATIONS OF CELLS, ELECTRICAL HEATING AND POWER

A cell converts chemical energy into electrical energy.

4.1 Electro motive force (E. M. F.)

The potential difference across the terminals of a cell when it is not delivering any current is called emf of the cell. The energy given by the cell in the flow of unit charge in the whole circuit (including the cell) is called the emf of the cell.

- emf depends on :
 - (i) nature of electrolyte
 - (ii) metal of electrodes
- emf does not depend on :
 - (i) area of plates
 - (ii) distance between the electrodes
 - (iii) quantity of electrolyte
 - (iv) size of cell

4.2 Internal resistance

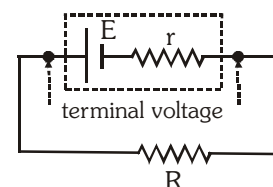
Resistance offered by the electrolyte of the cell when an electric current flows through it, is known as internal resistance.

- Distance between two electrodes increases \Rightarrow r increases
- Area dipped in electrolyte increases \Rightarrow r decreases
- Concentration of electrolyte increases \Rightarrow r increases
- Temperature increases \Rightarrow r decreases



4.3 Terminal potential difference (V)

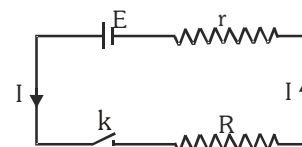
- When current is drawn through a cell or current is supplied to it then, the potential difference across its terminals is called terminal voltage.
- When I current is drawn from cell, then terminal voltage V is less than its e.m.f i.e., $V = E - Ir$



(a) When cell is discharging :

Current inside the cell is from cathode to anode.

$$\text{Current } I = \frac{E}{r + R} \Rightarrow E = IR + Ir = V + Ir \Rightarrow V = E - Ir$$

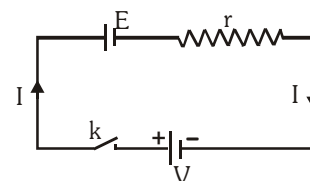


When current is drawn from the cell potential difference is less than the emf of the cell. Greater is the current drawn from the cell smaller is the terminal potential difference. When a large current is drawn from a cell its terminal potential difference is reduced appreciably.

(b) When cell is getting charged :

Current inside the cell is from anode to cathode.

$$\text{Current } I = \frac{V - E}{r} \Rightarrow V = E + Ir$$



During charging terminal potential difference is greater than the emf of the cell.



(c) When cell is in the open circuit :

$$\text{In open circuit } R = \infty \quad \therefore I = \frac{E}{R+r} = 0 \Rightarrow V = E$$

In open circuit, terminal potential difference is equal to emf and is the maximum potential difference which a cell can provide.

(d) When cell is short circuited :

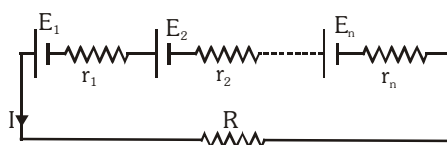
$$\text{In short circuit } R = 0 \Rightarrow I = \frac{E}{R+r} = \frac{E}{r} \text{ and } V = IR = 0$$

Note : In short circuit, current from the cell is maximum and terminal potential difference is zero.

4.4 Combination of cells

• Series combination

When cells are connected in series the total e.m.f. of the series combination is equal to the sum of the e.m.f.'s of the individual cells and the internal resistance of the cells will also be in series.



Equivalent internal resistance $r = r_1 + r_2 + r_3 + \dots$ Equivalent emf $E = E_1 + E_2 + E_3 + \dots$

$$\text{Current } I = \frac{E_{\text{net}}}{r_{\text{net}} + R}, \quad \text{If all } n \text{ cells are identical then } I = \frac{nE}{nr + R}$$

- If $nr \gg R$, $I = \frac{E}{r} \approx$ current from any cell when short-circuited.
- If $nr \ll R$, $I = \frac{nE}{R} \approx n \times$ current from any one cell, when connected with the external resistance.

• Parallel combination

When the cells are connected in parallel, the total e.m.f. of the parallel combination remains equal to the e.m.f. of a single equivalent cell and internal resistance of the cells will also be in parallel. If m identical cells connected in parallel then total internal resistance of this combination $r_{\text{net}} = \frac{r}{m}$. Total e.m.f. of this combination $= E$

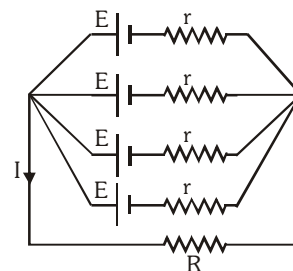
$$\text{Current in the circuit } I = \frac{E}{R + \frac{r}{m}} = \frac{mE}{mR + r}$$

If $r \ll mR$

$I = E/R =$ Current from any one cell when connected with the external resistance

If $r \gg mR$

$$I = \frac{mE}{r} = m \times \text{current from any cell when short-circuited}$$



- Mixed combination of identical cells**

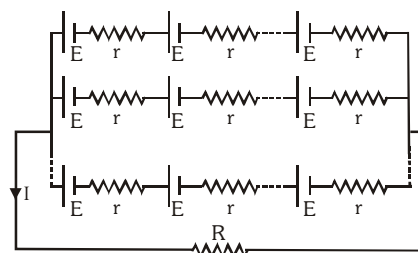
If n identical cells are connected in series and there are m such branches in the circuit then the total number of cells in this circuit is nm . The internal resistance of the cells connected in a row $= nr$.

Since there are m such rows,

$$\text{Total internal resistance of the circuit } r_{\text{net}} = \frac{nr}{m}$$

Total e.m.f. of the circuit = total e.m.f. of the cells connected in a row $E_{\text{net}} = nE$

$$\text{Current in the circuit } I = \frac{E_{\text{net}}}{R + r_{\text{net}}} = \frac{nE}{R + \frac{nr}{m}}$$



Note : Current I in the circuit is maximum when external resistance in the circuit is equal to the total internal resistance

$$\text{of the cells } R = \frac{nr}{m}.$$

4.5 Electrical Heating and Power

Cause of Heating

The potential difference applied across the two ends of a conductor sets up an electric field. Under the effect of electric field, electrons accelerate and as they move, they collide against the ions and atoms in the conductor, the energy of electrons transferred to the atoms and ions appear as heat.

- Joules's Law of Heating**

When a current I is made to flow through a ohmic resistance R for time t , heat Q is produced such that

$$Q = I^2 R t = P \times t = V I t = \frac{V^2}{R} t$$

Heat produced in a conductor does not depend upon the direction of current.

SI unit : joule ;

Practical Units : 1 kilowatt hour (kWh)

$$1\text{kWh} = 3.6 \times 10^6 \text{ joules} = 1 \text{ unit}$$

$$1 \text{ BTU (British Thermal Unit)} = 1055 \text{ J}$$

- Power :** $P = V I = \frac{V^2}{R} = I^2 R$

SI unit : Watt

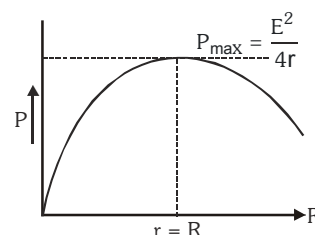
The watt-hour meter placed on the premises of every consumer records the electrical energy consumed.

- Power transferred to load by cell :**

$$P = I^2 R = \frac{E^2 R}{(r + R)^2} \quad \Rightarrow P = P_{\text{max}} \quad \text{if } \frac{dP}{dR} = 0 \Rightarrow r = R$$

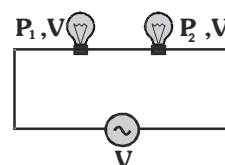
Power transferred by cell to load is maximum when

$$r = R \text{ and } P_{\text{max}} = \frac{E^2}{4r} = \frac{E^2}{4R}$$



- Series combination of resistors (bulbs)**

(a) Total power consumed $P_{\text{total}} = \frac{P_1 P_2}{P_1 + P_2}$. If n bulbs are identical $P_{\text{total}} = \frac{P}{n}$



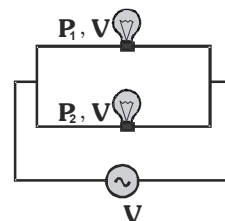
(b) In series combination of bulbs, Brightness \propto Power consumed by bulb $\propto R \propto \frac{1}{P_{\text{rated}}}$

Bulb of lesser wattage will shine more.

(c) For same current $P = I^2 R$ so $P \propto R$ $R \uparrow \Rightarrow P \uparrow$

- Parallel combination of resistors (bulbs)**

(a) Total power consumed $P_{\text{total}} = P_1 + P_2$. If n bulbs are identical $P_{\text{total}} = nP$



(b) In parallel combination of bulbs

Brightness \propto power consumed by bulb $\propto I \propto 1/R \Rightarrow$ Bulb of greater wattage will shine more.

(c) For same V more power will be consumed in smaller resistance $P \propto \frac{1}{R}$

(d) Two identical heater coils generate a total heat H_s when connected in series and H_p when connected in parallel then, $\frac{H_p}{H_s} = 4$ [In this it is assumed that supply voltage is same]

(e) If a heater boils m kg of water in time T_1 and another heater boils the same amount of water in time T_2 , then both connected in series will boil the same amount of water in time $T_s = T_1 + T_2$ and in parallel

$$T_p = \frac{T_1 T_2}{T_1 + T_2} \text{ [Use, time taken } \propto \text{ Resistance]}$$

(f) Instruments based on heating effects of current, work with both A.C. and D.C. Equal values of A.C. (RMS) and D.C. produce, equal heating effect. Due to this reason, the brightness of bulb is same whether it is operated by A.C. or an equivalent D.C.

GOLDEN KEY POINTS

- At the time of charging a cell, when current is supplied to it, the terminal voltage is greater than the e.m.f. E

$$V = E + Ir \quad \text{So} \quad V > E$$

- Series combination is useful when internal resistance of the cell is less than external resistance.
- Parallel combination is useful when internal resistance of the cell is greater than external resistance.
- Power in R (given resistance) is maximum, if its value is equal to the net resistance of remaining circuit.
- Internal resistance of an ideal cell = 0
- If external resistance is zero, then current delivered by the battery is maximum.



Illustrations

Illustration 22.

A battery of e.m.f. 2 volts and internal resistance 0.1Ω is being charged with a current of 5 A. Calculate the potential difference between the terminals of the battery.

Solution

Potential drop across internal resistance = $Ir = 0.1 \times 5 = 0.5 \text{ V}$

Hence potential difference across the terminals = $E + Ir = 2 + 0.5 = 2.5 \text{ volts}$.

Illustration 23.

A battery of six cells each of e.m.f. 2 V and internal resistance 0.5Ω is being charged by D. C. mains of e.m.f. 220 V by using an external resistance of 10Ω . What will be the charging current ?

Solution

Net e.m.f of the battery = 12 V and total internal resistance = 3Ω

Total resistance of the circuit = $3 + 10 = 13 \Omega$

$$I = \frac{\text{Net e.m.f.}}{\text{total resistance}} = \frac{220 - 12}{13} = 16 \text{ A}$$

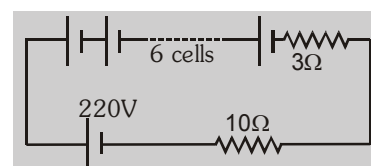


Illustration 24.

A battery of six cells each of e.m.f. 2 V and internal resistance 0.5Ω is being charged by D. C. mains of e.m.f. 220 V by using an external resistance of 10Ω . What is the potential difference across the battery ?

Solution

In case of charging of battery, terminal potential $V = E + Ir = 12 + 16 \times 3 = 60 \text{ volts}$.

Illustration 25.

Four identical cells each of e.m.f. 2 V are joined in parallel providing current to an external circuit consisting of two 15Ω resistors joined in parallel. The terminal voltage of the equivalent cell as read by an ideal voltmeter is 1.6 V. Calculate the internal resistance of each cell.

Solution

Total internal resistance of the cell combination $r_{eq} = \frac{r}{4}$

Total e.m.f. $E_{eq} = 2 \text{ V}$

Total external resistance $R = \frac{15 \times 15}{15 + 15} = \frac{15}{2} = 7.5 \Omega$

Current drawn from the equivalent cell $I = \frac{\text{terminal potential}}{\text{external resistance}} = \frac{1.6}{7.5} \text{ A}$

$$\therefore E - I \left(\frac{r}{4} \right) = 1.6 \quad \therefore 2 - \frac{1.6}{7.5} \left(\frac{r}{4} \right) = 1.6$$

$$\Rightarrow r = 7.5 \Omega$$

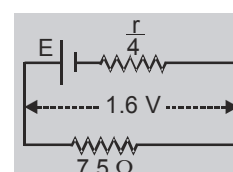
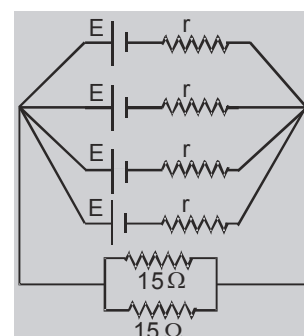


Illustration 26.

The e.m.f. of a primary cell is 2 V; when it is shorted it gives a current of 4 A. Calculate its internal resistance.

Solution

$$I = \frac{E}{r + R}$$

If cell is shorted then $R = 0$

$$I = \frac{E}{r} \quad \therefore \quad r = \frac{E}{I} = \frac{2}{4} = 0.5 \, \Omega$$

Illustration 27.

n rows each containing m cells in series, are joined in parallel. Maximum current is drawn from this combination in a $3 \, \Omega$ resistance. If the total number of cells used is 24 and the internal resistance of each cell is $0.5 \, \Omega$, find the values of m and n .

Solution

Total number of cells = $mn = 24$

For maximum current $\frac{mr}{n} = R \Rightarrow 0.5 m = 3 n$

$$\Rightarrow m = \frac{3n}{0.5} = 6n$$

$$\therefore 6n \times n = 24 \Rightarrow n = 2$$

$$\text{and } m \times 2 = 24 \Rightarrow m = 12$$

Illustration 28.

The e.m.f. of a cell is 6 volts. When 2 amperes current is drawn from it then the potential difference across its terminal remains 3 volts. Find its internal resistance.

Solution

$$\text{Internal resistance } r = \frac{E - V}{I} = \frac{6 - 3}{2} = 1.5 \, \Omega$$

Illustration 29.

An electric heater and an electric bulb are rated 500 W, 220 V and 100 W, 220 V respectively. Both are connected in series to a 220 V a.c. mains. Calculate the power consumed by (i) heater (ii) bulb.

Solution

$$P = \frac{V^2}{R} \text{ or } R = \frac{V^2}{P}, \text{ For heater, Resistance } R_h = \frac{(220)^2}{500} = 96.8 \, \Omega. \text{ For bulb, resistance } R_L = \frac{(220)^2}{100} = 484 \, \Omega$$

$$\text{Current in the circuit when both are connected in series } I = \frac{V}{R_L + R_h} = \frac{220}{484 + 96.8} = 0.38 \, \text{A}$$

$$(i) \text{ Power consumed by heater } = I^2 R_h = (0.38)^2 \times 96.8 = 13.98 \, \text{W}$$

$$(ii) \text{ Power consumed by bulb } = I^2 R_L = (0.38)^2 \times 484 = 69.89 \, \text{W}$$



Illustration 30.

A heater coil is rated 100 W, 200 V. It is cut into two identical parts. Both parts are connected together in parallel to the same source of 200 V. Calculate the energy liberated per second in the new combination.

Solution

$$\therefore P = \frac{V^2}{R} \quad \therefore R = \frac{V^2}{P} = \frac{(200)^2}{100} = 400 \, \Omega$$

$$\text{Resistance of half piece} = \frac{400}{2} = 200 \, \Omega$$

$$\text{Resistance of pieces connected in parallel} = \frac{200}{2} = 100 \, \Omega$$

$$\text{Energy liberated/second } P = \frac{V^2}{R} = \frac{200 \times 200}{100} = 400 \, \text{W}$$

Illustration 31.

The power of a heater is 500 W at 800 °C. What will be its power at 200 °C. If $\alpha = 4 \times 10^{-4}$ per °C ?

$$\text{Solution } P = \frac{V^2}{R} \quad \therefore \frac{P_{200}}{P_{800}} = \frac{R_{800}}{R_{200}} = \frac{R_0(1 + 4 \times 10^{-4} \times 800)}{R_0(1 + 4 \times 10^{-4} \times 200)} \Rightarrow P_{200} = \frac{500 \times 1.32}{1.08} = 611 \, \text{W}$$

Illustration 32.

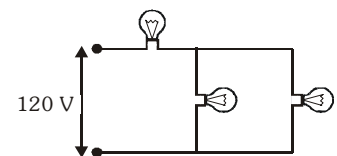
When a battery sends current through a resistance R_1 for time t , the heat produced in the resistor is Q . When the same battery sends current through another resistance R_2 for time t , the heat produced in R_2 is again Q . Determine the internal resistance of the battery.

Solution

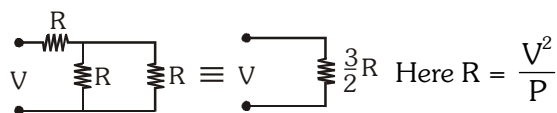
$$\left[\frac{E}{R_1 + r} \right]^2 R_1 = \left[\frac{E}{R_2 + r} \right]^2 R_2 \Rightarrow r = \sqrt{R_1 R_2}$$

Illustration 33.

Three 60 W, 120 V light bulbs are connected across a 120 V power source. If the resistance of each bulb does not change with current then find out the total power delivered to the three bulbs.



- (A) 180 W (B) 20 W (C) 40 W (D) 60 W

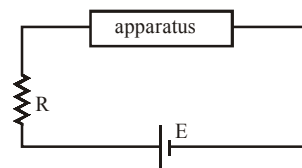
Solution**Ans. (C)**

$$\text{Total power supplied} = \frac{V^2}{\left(\frac{3}{2}\right)R} = \left(\frac{2}{3}\right) \left(\frac{V^2}{R}\right) = \frac{2}{3} \times 60 = 40 \, \text{W}$$



Illustration 34.

An apparatus is connected to an ideal battery as shown in figure. For what value of current, power delivered to the apparatus will be maximum?



(A) $\frac{E}{R}$

(B) $\frac{E}{2R}$

(C) $\frac{E}{4R}$

(D) information is insufficient

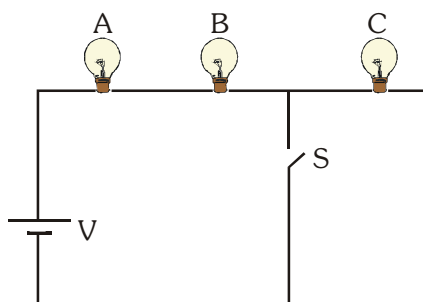
Solution

Ans. (B)

For maximum power $R_{\text{ext}} = R_{\text{int}} = R \therefore \text{current} = \frac{E}{2R}$

Illustration 35.

Three identical bulbs are connected in a circuit as shown. What will happen to the brightness of bulbs A & B if the switch is closed ?

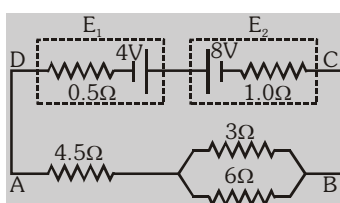
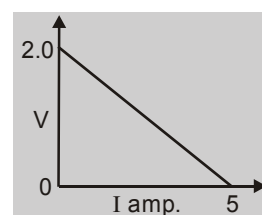


Solution

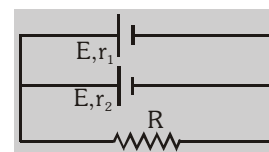
When switch S is closed, current does not pass through bulb C. Hence total resistance decreases & current passing through bulbs A & B increases. Brightness of bulbs A & B also increases.

BEGINNER'S BOX-4

1. A battery of 20 cells (each having e.m.f. 1.8 V and internal resistance 0.1Ω) is charged by 220 volts and the charging current is 15 A. Calculate the resistance to be put in the circuit.
2. For a cell, the graph between the potential difference (V) across the terminals of the cells and the current I drawn from the cell is as shown in figure. Calculate the e.m.f. and the internal resistance of the cell.
3. In the given circuit, calculate the value of current in the 4.5Ω resistor and indicate its direction. Also calculate the potential difference across each cell.



4. Two cells of equal e.m.f. E but of different internal resistances r_1 and r_2 are connected in parallel and the combination is connected with an external resistance R to obtain maximum power in R . Find the value of R .
5. What is the largest voltage you can safely apply across a resistor marked 196Ω ; $1W$?
6. Two bulbs whose resistances are in the ratio $1:2$ are connected in parallel to a source of constant voltage. What will be the ratio of the power dissipation in these?



5. MEASURING DEVICES

5.1 Galvanometer

The instrument used to measure strength of current, by measuring the deflection of the coil due to torque produced by a magnetic field, is known as galvanometer.

Shunt

The small resistance connected in parallel to a galvanometer coil, in order to control the current flowing through the galvanometer, is known as shunt.

Merits of shunt

- (i) To protect the galvanometer coil from burning.
- (ii) Any galvanometer can be converted into ammeter of desired range with the help of suitable shunt.
- (iii) The resistance of ammeter decreases due to shunt, thereby affecting the observed current to a lesser extent.

Demerits of shunt

Shunt resistance decreases the sensitivity of galvanometer.

Conversion of Galvanometer into Ammeter

A galvanometer can be converted into an ammeter by connecting a low resistance (shunt) in parallel to its coil.

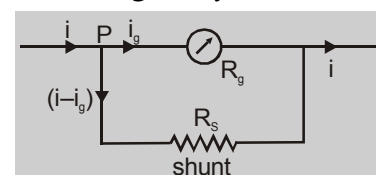
- The value of shunt resistance to be connected in parallel to galvanometer coil is given by -

$$R_S = \frac{R_g i_g}{i - i_g}$$

Where i = Range of ammeter

i_g = Current required for full scale deflection of galvanometer.

R_g = Resistance of galvanometer coil.



- $R_S = \frac{R_g i_g}{i}$ if $i_g \ll i$

Where

- The length of shunt wire $\ell = \frac{\pi r^2 R_S}{\rho}$

$$\left[\begin{array}{l} r = \text{radius of wire} \\ R_S = \text{resistance of shunt wire} \\ \rho = \text{specific resistance of material of wire.} \end{array} \right.$$

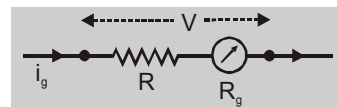
- On connecting shunt in parallel to a galvanometer coil, the equivalent resistance becomes less than even the shunt resistance.



Conversion of galvanometer into voltmeter

- A galvanometer can be converted into a voltmeter by connecting a high resistance in series with its coil.
- The high resistance to be connected in series with galvanometer coil is given by -

$$R = \frac{V}{i_g} - R_g$$



- If R_g is negligible, then $R = \frac{V}{i_g}$

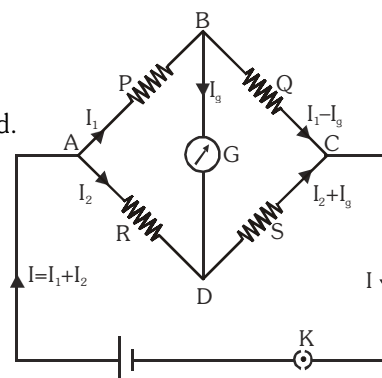
5.2 Wheat stone bridge

Wheatstone bridge devised by Charles Wheatstone in 1843 is an arrangement of four resistances which can be used to determine one of them in terms of the rest.

- The configuration in the adjacent figure is called Wheat stone bridge.
- If current in galvanometer is zero ($I_g = 0$) then bridge is said to be balanced.

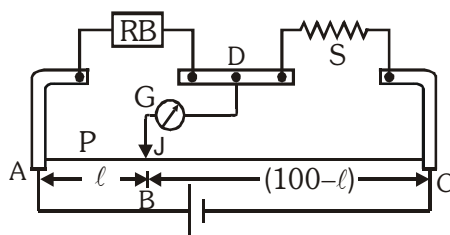
$$V_D = V_B \Rightarrow I_1 P = I_2 R \text{ \& } I_1 Q = I_2 S \Rightarrow \frac{P}{Q} = \frac{R}{S}$$

- If $\frac{P}{Q} < \frac{R}{S}$ then $V_B > V_D$ and current will flow from B to D.
- If $\frac{P}{Q} > \frac{R}{S}$ then $V_B < V_D$ and current will flow from D to B.



5.3 Meter Bridge

It is based on the principle of wheatstone bridge. It is used to find out unknown resistance of wire. AC is a 1 m long uniform wire. R.B. (Resistance Box) is a known resistance and S is an unknown resistance. A cell is connected across the 1 m long wire and Galvanometer is connected between Jockey and midpoint D. To find out the unknown resistance the jockey made to touch from A to C and balanced condition is found. Let balance is at B point on wire.



$$AB = l \text{ cm}$$

$$P = r l$$

$$BC = (100 - l) \text{ cm}$$

$$Q = r (100 - l) \quad \text{where } r = \text{resistance per unit length of wire.}$$

$$\text{In the balanced condition : } \frac{P}{Q} = \frac{R}{S} \Rightarrow \frac{r l}{r (100 - l)} = \frac{R}{S}$$

$$\Rightarrow S = \frac{(100 - l)}{l} R$$



GOLDEN KEY POINTS

- The rate of variation of deflection depends upon the magnitude of deflection itself and hence on the accuracy of the instrument.
- A suspended coil galvanometer can measure currents of the order of 10^{-9} amperes.
- I_g is the current for full scale deflection. If the current corresponding to a deflection of one division on the galvanometer scale is k and N is the total number of divisions on one side of the zero of galvanometer scale, then $I_g = k \times N$.
- A ballastic galvanometer is a specially designed moving coil galvanometer, used to measure charge flowing through a circuit for a small time interval.
- To increase the range of an ammeter a shunt is connected in parallel with the galvanometer.
- To convert an ammeter of range I amperes and resistance $R_g \Omega$ into an ammeter of range nI amperes, the value of resistance to be connected in parallel will be $\frac{R_g}{n-1} \Omega$.
- To increase the range of a voltmeter a high resistance is connected in series with it.
- To convert a voltmeter of resistance $R_g \Omega$ and range V volts into a voltmeter of range nV volts, the value of resistance to be connected in series will be $(n-1)R_g \Omega$.
- Resistance of ideal ammeter is zero & resistance of ideal voltmeter is infinite.
- The wheatstone bridge is most sensitive when the resistances in all its four branches of same order are almost equal.

Illustrations

Illustration 36.

A 100 volts voltmeter whose resistance is $20 \text{ k}\Omega$ is connected in series with a very high resistance R . When it is joined across a line of 110 volts, it reads 5 volts. What is the magnitude of resistance R ?

Solution

When the voltmeter is connected across 110 volts line, current through the voltmeter $I = \frac{110}{(20 \times 10^3 + R)}$

Potential difference across the voltmeter $V = IR_v \Rightarrow 5 = \frac{110 \times 20 \times 10^3}{(20 \times 10^3 + R)}$

$\Rightarrow 20 \times 10^3 + R = 440 \times 10^3 \Rightarrow R = 420 \times 10^3 \Omega$

Illustration 37.

A galvanometer having 30 divisions has current sensitivity of $20 \mu\text{A}/\text{division}$. It has a resistance of 25Ω .

- How will you convert it into an ammeter measuring currents upto 1 ampere?
- How will you convert this galvanometer into a voltmeter measuring voltages upto 1 volt?

Solution

The current required for full scale deflection $I_g = 20 \mu\text{A} \times 30 = 600 \mu\text{A} = 6 \times 10^{-4} \text{A}$

- To convert it into ammeter, a shunt is required in parallel with it.

Shunt resistance $R_s = \frac{I_g R_g}{(I - I_g)} = \left(\frac{6 \times 10^{-4}}{1 - 6 \times 10^{-4}} \right) 25 = 0.015 \Omega$

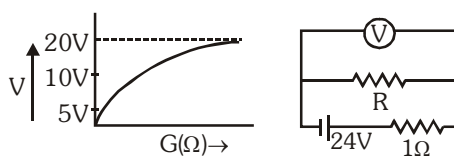
- To convert the galvanometer into a voltmeter, a high resistance is required in series with it.

series resistance $R = \frac{V}{i_g} - R_g = \frac{1}{6 \times 10^{-4}} - 25 = 1666.67 - 25 = 1641.67 \Omega$



Illustration 38.

A cell of internal resistance 1Ω is connected across a resistor R . A voltmeter having variable resistance is used to measure the potential difference across the resistor. The plot of voltmeter reading V against G is shown. What is value of external resistor R ? (G = Resistance of galvanometer)



(A) 5Ω

(B) 4Ω

(C) 3Ω

(D) cannot be determined

Solution

Ans. (A)

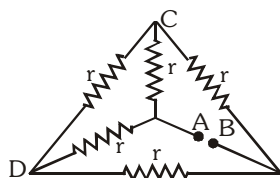
When galvanometer resistance tends to infinity $G \rightarrow \infty$,

Potential difference across R is $20V \Rightarrow 20 = 24 - i \times 1 \Rightarrow i = 4\text{ A}$.

Also $20 = 4 \times R \Rightarrow R = 5\Omega$.

Illustration 39.

In the adjoining network of resistors each has resistance r . Find the equivalent resistance between the points A and B .



Solution

Given circuit is a balanced Wheatstone Bridge $\therefore \frac{1}{R_{AB}} = \frac{1}{2r} + \frac{1}{2r} = \frac{1}{r}$ $R_{AB} = r$

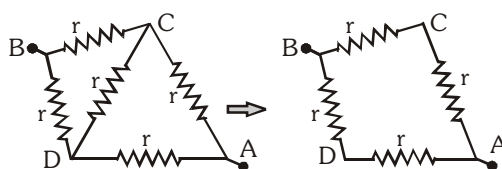
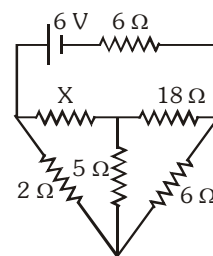


Illustration 40.

Calculate the magnitude of resistance X in the circuit shown in figure, when no current flows through the 5Ω resistor?



Solution

Since Wheatstone bridge is balanced so $\frac{x}{18} = \frac{2}{6}$ or $x = \frac{18 \times 2}{6} = 6\Omega$

Illustration 41.

In the following diagram the galvanometer shows zero deflection then what is the value of R ?

Solution

For a balanced Wheatstone bridge $\frac{100}{100R} = \frac{200}{(100+R)}$

$\Rightarrow \frac{100+R}{R} = 5 \Rightarrow 100 + R = 5R \Rightarrow R = \frac{100}{4} = 25\Omega$.

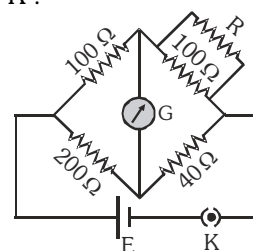
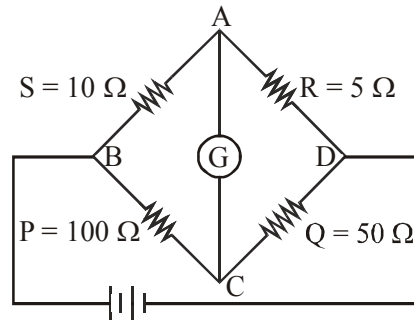


Illustration 42.

Figure shows a balanced Wheatstone's bridge

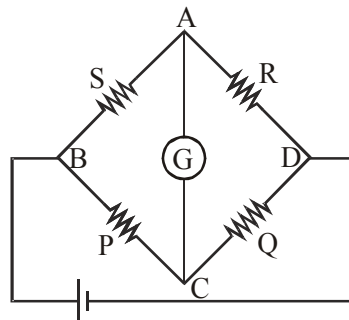


- (A) If P is slightly increased, the current in the galvanometer flows from C to A
 (B) If P is slightly increased, the current in the galvanometer flows from A to C
 (C) If Q is slightly increased, the current in the galvanometer flows from C to A
 (D) If Q is slightly increased, the current in the galvanometer flows from A to C

- (1) AB (2) BC (3) CD (4) AD

Solution

Ans. (2)

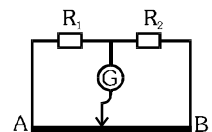


If P is slightly increased, potential of C will decrease. Hence current will flow from A to C. If Q is slightly increased, potential of C will increase, hence current will flow from C to A.

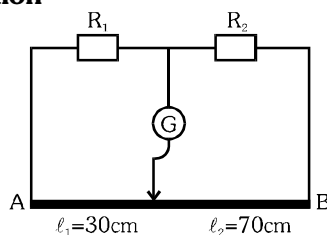
Illustration 43.

Consider a part of a meter bridge experiment as shown in figure When resistances in the two gaps are R_1 and R_2 then balancing length from end A is 30 cm. Now 10 Ω resistances are added in both gaps then balancing length becomes 40 cm. Calculate :

- (a) Ratio of $\frac{R_1}{R_2}$
 (b) Values of R_2 and R_1
 (c) Value of resistance to be added in R_1 so that the balancing point is at the mid point of the wire AB.



Solution

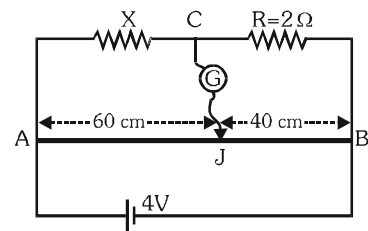


- (a) $\frac{R_1}{R_2} = \frac{l_1}{l_2} = \frac{30}{70} = \frac{3}{7}$
 (b) $\frac{R_1 + 10}{R_2 + 10} = \frac{40}{60} = \frac{2}{3} \Rightarrow 3R_1 + 30 = 2R_2 + 20$
 $\Rightarrow 3R_1 + 10 = 2 \times \frac{7R_1}{3} \Rightarrow R_1 = 6 \Omega \text{ \& } R_2 = 14 \Omega$
 (c) Assume that value of resistance added in R_1 is x
 $\therefore \frac{R_1 + x}{R_2} = \frac{50}{50} \Rightarrow 6 + x = 14 \Rightarrow x = 8 \Omega$



Illustration 44.

If no current flows through the galvanometer then find the value of the unknown resistance X . Assume that the resistance per unit length of the wire AB is $0.02 \Omega/\text{cm}$. Also calculate total current supplied by the battery.

**Solution**

For balanced condition $\frac{X}{R_{AJ}} = \frac{2}{R_{JB}}$

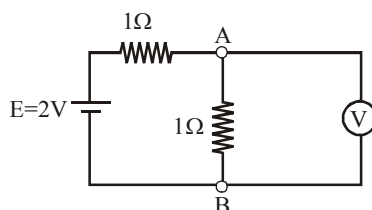
$$R_{AJ} = 0.02 \times 60 = 1.2 \Omega, R_{JB} = 0.02 \times 40 = 0.8 \Omega \Rightarrow \frac{X}{1.2} = \frac{2}{0.8} \Rightarrow X = 3 \Omega$$

Current supplied by the battery $I = \frac{4}{R_{eq}}$

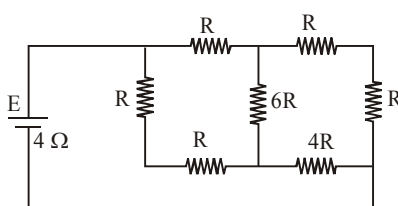
where net Resistance $R_{eq} = \frac{(3+2)(1.2+0.8)}{3+2+1.2+0.8} = \frac{10}{7} \Omega$ so $I = \frac{4 \times 7}{10} = 2.8 \text{ A}$

BEGINNER'S BOX-5

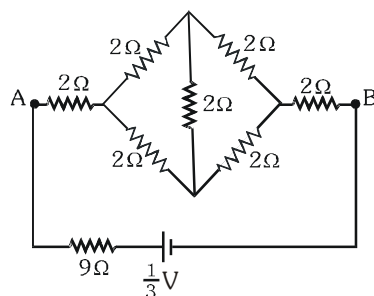
1. A galvanometer of resistance 100Ω gives full scale deflection for 10 mA current. What should be the value of shunt, so that it can measure currents upto 100 mA ?
2. The resistance of a moving coil galvanometer is 20Ω . It requires 0.01 A current for full scale deflection. Calculate the value of resistance required to convert it into a voltmeter of range 20 volts .
3. The resistance of an ammeter of range 5 A is 1.8Ω . A shunt of 0.2Ω is connected in parallel to it. When its indicator shows a current of 2 A then what will be the effective current?
4. A galvanometer of resistance 100Ω gives full scale deflection for a current of 10^{-5} A . Calculate the shunt required to convert it into an ammeter of 1 ampere range.
5. The shunt required for 10% of main current to be sent through a moving coil galvanometer of resistance 99Ω will be
6. In the given circuit, the voltmeter and the electric cell are ideal. Find the reading of the voltmeter (in volts)



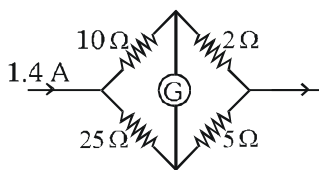
7. A battery of internal resistance 4Ω is connected to the network of resistances as shown in figure. In order that maximum power is delivered to the network, the value of R in Ω should be



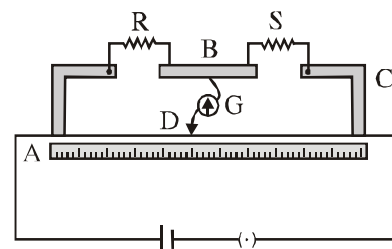
8. For the given circuit find out the –



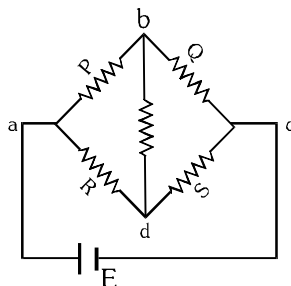
- (a) total resistance of the circuit across the battery terminals.
 (b) potential difference between A and B.
9. Calculate the current flowing through the resistance $2\ \Omega$.



10. Circuit diagram of metre bridge is shown in figure. The null point is found at a distance of 40 cm from A. If now a resistance of $12\ \Omega$ is connected in parallel with S, the null point shifts to 64 cm. Determine the values of R and S.



11. What is the relation between P, Q, R and S if current in the branch bd is



- (a) Zero ? (b) from b to d ?

6. POTENTIOMETER

6.1 Necessity of Potentiometer

Practically voltmeter has a finite resistance. (ideally it should be ∞) In other words, it draws certain current from the circuit. To overcome this problem a potentiometer is employed because at the instant of measurement, it draws no current from the circuit.

6.2 Working Principle of Potentiometer

Any unknown potential difference is balanced on a known potential difference which is uniformly distributed over the entire length of a potentiometer wire.

This process is termed as zero deflection or null deflection method.

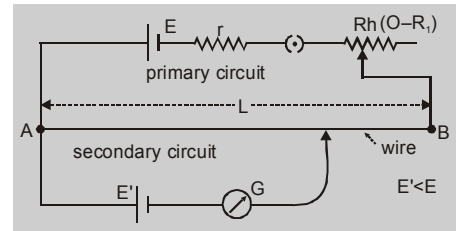
Note :

- Potentiometer wire : Made up of alloys of manganin, constantan, Eureka.
- Special properties of these alloys are high specific resistance, negligible temperature co-efficient of resistance (α). This results in invariability of resistance of potentiometer wire over a long period.



6.3 Circuits of Potentiometer

- Primary circuit contains source of constant voltage & rheostat or Resistance Box.
- Secondary circuit contains battery & galvanometer.



Potential gradient (x) (V/m)

- Potential difference corresponding to unit length of potentiometer wire is called potential gradient.
- Rate of growth/fall of potential per unit length of potentiometer wire is equal to potential gradient.

Let $r = 0$ and $R_1 = 0$ then $V_{AB} = E$ (max. in the ideal case) then $x = E/L$

Unit and dimensions : (V/m ; $MLT^{-3}A^{-1}$)

- Always $V_{AB} < E$; ($\because r + R_1 \neq 0$)

$$x = \frac{V_{AB}}{L} \quad \text{Now } V_{AB} = I R_p \quad (R_p = \text{resistance of potentiometer wire})$$

Let ρ = Resistance per unit length of potentiometer wire

$$\text{So } x = \frac{I R_p}{L} = I \rho \quad \rho = \frac{R_p}{L}$$

$$\text{current in primary circuit } I = \frac{E}{R_1 + r + R_p} ; \quad x = \frac{E}{R_1 + R_p + r} \left(\frac{R_p}{L} \right)$$

- If cross-sectional radius is uniform $\Rightarrow x$ is uniform over the entire length of potentiometer wire.
- If I constant, then $x \propto \frac{1}{(\text{radius})^2}$
- 'x' depends on $\rightarrow \rho, r, \sigma$ etc.

Factors affecting 'x'

- If V_{AB} = constant and L = constant then for any change $\rightarrow x$ remains unchanged.
- If there is no information about V_{AB} then always take V_{AB} as constant so ($x \propto 1/L$)
- If V_{AB} and L are constant :

For any change like radius of wire, substance of wire (σ) there is no change in x .

- Any change in the secondary circuit results in no change in x because x is an element of primary circuit.

Note : $x = \frac{E}{R_p + r + R_1} \left(\frac{R_p}{L} \right)$

x_{\max} or x_{\min} on the basis of range of rheostat or resistance box (R.B.)

$$\text{If } R_1 = 0 \Rightarrow x_{\max} = \frac{E}{R_p} \times \frac{R_p}{L} \quad (r \approx 0)$$

$$\text{If } R_1 = R \Rightarrow x_{\min} = \frac{E}{R_p + R} \left(\frac{R_p}{L} \right) \quad \text{then } \frac{x_{\max}}{x_{\min}} = \frac{R_p + R}{R_p}$$



6.4 Standardization and Sensitivity of Potentiometer

Standardization process of evaluating x experimentally :

If balanced length for a standard cell (emf E) is $= \ell_0$ then potential gradient $x = \frac{E}{\ell_0}$

Sensitivity :

- x is also a measure of the sensitivity of potentiometer.
- If $x \downarrow \Rightarrow$ sensitivity \uparrow
- To increase sensitivity $\rightarrow R_h \uparrow$ (current in primary circuit should be reduced), $L \uparrow$
- Any change in secondary circuit has no effect on sensitivity.
- Balanced length for unknown potential difference $\uparrow \Rightarrow$ sensitivity \uparrow

7. APPLICATIONS OF POTENTIOMETER

- To measure the potential difference across a resistance.
- To find out the emf of a cell.
- Comparison of two emfs $\frac{E_1}{E_2}$
- To find out the internal resistance of a primary cell.
- Comparison of two resistances.
- To find out the current in a given circuit.

7.1 Comparison of emfs of Two Cells

plug only in (1- 2)

plug only in (2 - 3)

Jockey is at position J

Jockey is at position J'

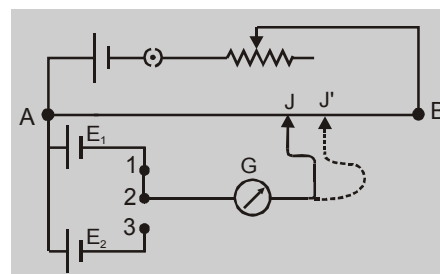
balance length $AJ = \ell_1$

balance length $AJ' = \ell_2$

$E_1 = x\ell_1$

$E_2 = x\ell_2$

$$\Rightarrow \frac{E_1}{E_2} = \frac{\ell_1}{\ell_2}$$



7.2 Internal Resistance of a Given Primary Cell

$$E = V + Ir \Rightarrow r = \frac{E - V}{I}$$

$$\text{or } r = \left(\frac{E - V}{V} \right) R$$

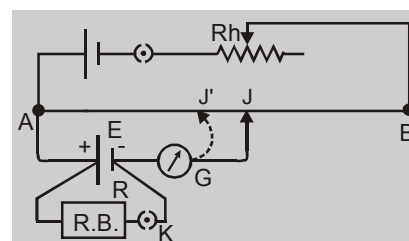
Key K open

$$E = x\ell_1 \quad (AJ = \ell_1)$$

Key K closed terminal potential difference

$$V = x\ell_2 \quad (AJ' = \ell_2)$$

$$r = \left(\frac{\ell_1 - \ell_2}{\ell_2} \right) R$$



7.3 Comparison of Two Resistances

Plug only in (1-2)

potential difference across R_1 is balanced

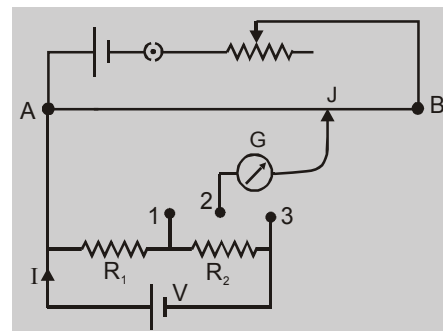
$$\therefore I R_1 = x \ell_1$$

Plug only in (2-3)

potential difference across $(R_1 + R_2)$ is balanced

$$\therefore I (R_1 + R_2) = x \ell_2$$

$$\frac{R_1 + R_2}{R_1} = \frac{\ell_2}{\ell_1} \Rightarrow \frac{R_2}{R_1} = \frac{\ell_2 - \ell_1}{\ell_1}$$



7.4 Measurement of Current

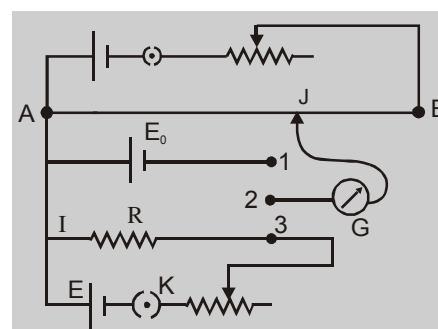
Plug only in (1-2)

$$E_0 = x \ell_0$$

Plug only in (2-3)

$$V = I R = x \ell_1$$

$$I = \frac{\ell_1}{R} \times \frac{E_0}{\ell_0}$$



GOLDEN KEY POINTS

- The effective resistance of potentiometer is infinite.
- The rate of variation of deflection depends upon the magnitude of deflection itself and hence on the accuracy of the instrument.

<i>Difference between potentiometer and voltmeter</i>	
Potentiometer	Voltmeter
<ul style="list-style-type: none"> • It measures the unknown emf very accurately • While measuring emf it does not draw any current from the driving source of emf. • While measuring unknown potential difference the resistance of potentiometer becomes infinite. • It is based on zero deflection method. • It has a high sensitivity. • it is used for various applications like measurement of internal resistance of cell, calibration of ammeter and voltmeter, measurement of thermo emf, comparison of emf's etc. 	<ul style="list-style-type: none"> • It measures the unknown emf approximately. • While measuring emf it draws some current from the source of emf. • While measuring unknown potential difference the resistance of voltmeter is high but finite. • It is based on deflection method. • Its sensitivity is low. • It is only used to measured emf or unknown potential difference.

Illustrations

Illustration 45.

There is a definite potential difference between the two ends of a potentiometer. Two cells are connected in such a way that the first time they support each other, and the second time they oppose each other. They are balanced on the potentiometer wire over a 120 cm and 60 cm length respectively. Compare the electromotive forces of the cells.



Solution

Suppose the potential gradient along the potentiometer wire = x and the emf's of the two cells are E_1 and E_2 .

When the cells support each other, the resultant emf = $(E_1 + E_2)$ $\therefore E_1 + E_2 = x \times 120 \text{ cm} \dots(i)$

When the cells oppose each other, the resultant emf = $(E_1 - E_2)$ $\therefore E_1 - E_2 = x \times 60 \text{ cm} \dots(ii)$

$$\text{From equation (i) and (ii)} \quad \frac{E_1 + E_2}{E_1 - E_2} = \frac{120 \text{ cm}}{60 \text{ cm}} = \frac{2}{1}$$

$$\Rightarrow E_1 + E_2 = 2(E_1 - E_2)$$

$$\Rightarrow 3E_2 = E_1$$

$$\Rightarrow \frac{E_1}{E_2} = \frac{3}{1}$$

Illustration 46.

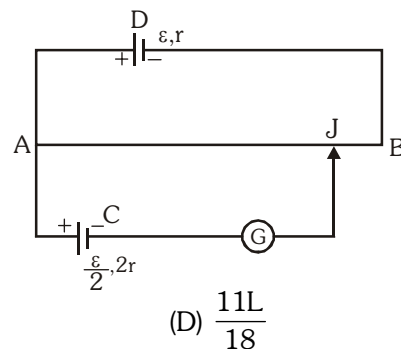
In the figure, the potentiometer wire AB of length L and resistance $9r$ is joined to the cell D of emf ε and internal resistance r . The cell C's emf is $\frac{\varepsilon}{2}$ and its internal resistance is $2r$. The galvanometer G will show no deflection when the length AJ is

(A) $\frac{4L}{9}$

(B) $\frac{5L}{9}$

(C) $\frac{7L}{18}$

(D) $\frac{11L}{18}$



Ans. (B)

Solution

$$\text{Potential gradient } x = \left(\frac{E}{10r} \right) \left(\frac{9r}{L} \right)$$

According to question

$$\frac{E}{2} = \left(\frac{E}{10r} \right) \left(\frac{9r}{L} \right) (\ell) \Rightarrow \ell = \frac{5L}{9}$$

Illustration 47.

In the given potentiometer circuit length of the wire AB is 3m and resistance is $R=4.5\Omega$. The length AC for no deflection in galvanometer is

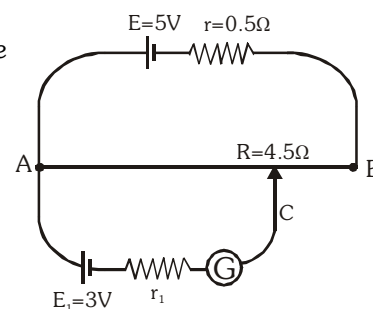
(A) 2m

(B) 1.8m

(C) dependent on r_1

(D) None of these

Ans. (A)



Solution

Potential gradient

$$x = \left(\frac{5}{0.5 + 4.5} \right) \left(\frac{4.5}{3} \right) = 1.5 \text{ Vm}^{-1}$$

$$\text{Here } (x)(AC) = 3 \Rightarrow AC = \frac{3}{1.5} = 2\text{m}$$



BEGINNER'S BOX-6

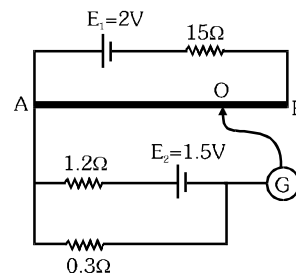
1. The length of a potentiometer wire is ℓ . A cell of emf E is balanced at a length $\ell/3$ from the positive end of the wire. If the length of the wire is increased by $\ell/2$ at what distance will the same cell give a balanced point

(A) $\frac{2\ell}{3}$ (B) $\frac{\ell}{2}$ (C) $\frac{\ell}{6}$ (D) $\frac{4\ell}{3}$

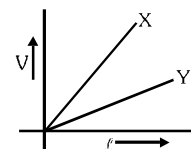
2. AB is 1 meter long uniform wire of 10 ohm resistance.

The other data are as shown in the circuit diagram. Calculate

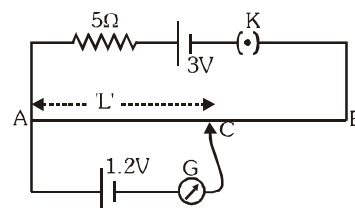
- (a) potential gradient along AB and
(b) length AO of the wire, when the galvanometer shows no deflection.



3. The variation of potential difference V with length ℓ in case of two potentiometers X and Y is as shown in the given diagram. Which one of these two will you prefer for comparing e.m.f.'s of two cells and why?



4. The potentiometer wire of length 100 cm has a resistance of 10Ω . It is connected in series with a resistance of 5Ω and an accumulator of emf 3V having negligible resistance. A source of 1.2 V is balanced against a length 'L' of the potentiometer wire. Find the value of L.



5. A 10 m long wire of resistance 20Ω is connected in series with a battery of e.m.f. 3V (negligible internal resistance) and a resistance of 10Ω . Find the potential gradient along the wire.



ANSWERS

BEGINNER'S BOX-1

1. $0.5 \times 10^{-16} \text{ A}$ 2. 2×10^{16}
3. 0.15 mm/s
4. 0.02 A ; $2.74 \times 10^{-12} \text{ m/s}$

BEGINNER'S BOX-2

1. $4 \times 10^{-4} \Omega$ 2. 0.4%
3. $R = 20 \Omega$,
Resistivity of the wire remains unchanged as it does not change with change in dimensions of a material without change in its temperature.
4. 273°C
5. (A) – q, (B) – p, (C) – r
6. (A) – s, (B) – p, (C) – q, (D) – r

BEGINNER'S BOX-3

1. $2R$ 2. $R_{AC} = \left(\frac{n^2 + 1}{n} \right) r$
3. $\frac{1}{100} \Omega$ 4. 40Ω
5. 3.7 A 6. 3 V

BEGINNER'S BOX-4

1. 10.27Ω 2. 2 V ; 0.4Ω
3. $I = 0.5 \text{ A}$, anticlockwise CDABC $E_1 = 4.25 \text{ V}$, $E_2 = 7.5 \text{ V}$
4. $\frac{r_1 r_2}{r_1 + r_2}$ 5. 14 volts 6. $\frac{P_1}{P_2} = \frac{2}{1}$

BEGINNER'S BOX-5

1. 11.11Ω 2. 1980Ω
3. 20 A 4. $10^{-3} \Omega$
5. 11Ω 6. 1 V
7. 2 8. (a) 15Ω , (b) 0.133 V
9. 1 A 10. $\frac{40}{3} \Omega$, 20Ω
11. (a) $\frac{P}{Q} = \frac{R}{S}$, (b) $\frac{R}{S} > \frac{P}{Q}$

BEGINNER'S BOX-6

1. (B)
2. (a) 0.8 V/m , (b) 37.5 cm
3. A potentiometer circuit in which the potential gradient is smaller will be preferred as it is more sensitive. In the graph shown $\frac{dV}{d\ell}$ is smaller for potentiometer Y and it will be preferred.
4. 60 cm
5. 0.2 V/m



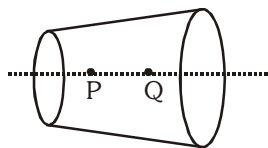
EXERCISE-I (Conceptual Questions)

ELECTRIC CURRENT & DRIFT VELOCITY

- If 10^6 electrons/s are flowing through an area of cross section of 10^{-4} m^2 then the current will be :-
(1) $1.6 \times 10^{-7} \text{ A}$ (2) $1.6 \times 10^{-13} \text{ A}$
(3) $1 \times 10^{-6} \text{ A}$ (4) $1 \times 10^2 \text{ A}$
- The current in a conductor varies with time t as $I = 2t + 3t^2 \text{ A}$ where I is amperes and t in seconds. Electric charge flowing through a section of the conductor during $t = 2 \text{ s}$ to $t = 3 \text{ s}$ is :-
(1) 10 C (2) 24 C
(3) 33 C (4) 44 C
- 10,000 electrons are passing per minute through a tube of radius 1cm. The resulting current is :
(1) 10000 A
(2) $0.25 \times 10^{-16} \text{ A}$
(3) 10^{-9} A
(4) $0.5 \times 10^{-19} \text{ A}$
- There are 8.4×10^{22} free electrons per cm^3 in copper. The current in the wire is 0.21 A ($e = 1.6 \times 10^{-19} \text{ C}$). Then the drifts velocity of electrons in a copper wire of 1 mm^2 cross section, will be :-
(1) $2.12 \times 10^{-5} \text{ m/s}$
(2) $0.78 \times 10^{-5} \text{ m/s}$
(3) $1.56 \times 10^{-5} \text{ m/s}$
(4) none of these
- There is a current of 40 amperes in a wire of 10^{-6} m^2 area of cross-section. If the number of free electrons per m^3 is 10^{29} , then the drift velocity will be
(1) $1.25 \times 10^3 \text{ m/s}$
(2) $2.50 \times 10^{-3} \text{ m/s}$
(3) $25.0 \times 10^{-3} \text{ m/s}$
(4) $250 \times 10^{-3} \text{ m/s}$
- S.I. unit of current is :-
(1) C (2) A
(3) A/s (4) N/s
- When no current flows through a conductor :-
(1) the free electrons do not move
(2) the average speed of a free electron over a large period of time is zero
(3) the average velocity of a free electron over a large period of time is zero
(4) the average of square of velocities of all the free electrons at an instant is zero
- A steady current flows in a metallic conductor of non-uniform cross-section. The quantity/quantities which remain constant along the length of the conductor is/are
(1) current, electric field and drift velocity
(2) drift speed only
(3) current and drift speed
(4) current only
- The number of free electrons per 10 mm of an ordinary copper wire is about 2×10^{21} . The average drift speed of the electrons is 0.25 mm/s The current flowing is :-
(1) 0.8 A (2) 8 A (3) 80 A (4) 5 A
- In a Neon discharge tube $2.9 \times 10^{18} \text{ Ne}^+$ ions move to the right each second, while 1.2×10^{18} electrons move to the left per second; electron charge is $1.6 \times 10^{-19} \text{ C}$. The current in the discharge tube is :-
(1) 1 A towards right
(2) 0.66 A towards right
(3) 0.66 A towards left
(4) zero
- Two wires each of radius of cross section r but of different materials are connected together end to end (in series). If the densities of charge carriers in the two wires are in the ratio 1:4, the drift velocity of electrons in the two wires will be in the ratio :
(1) 1 : 2 (2) 2 : 1
(3) 4 : 1 (4) 1 : 4
- A current I flows through a uniform wire of diameter d when the electron drift velocity is v . The same current will flow through a wire of diameter $d/2$ made of the same material if the drift velocity of the electrons is
(1) $v/4$ (2) $v/2$
(3) $2v$ (4) $4v$

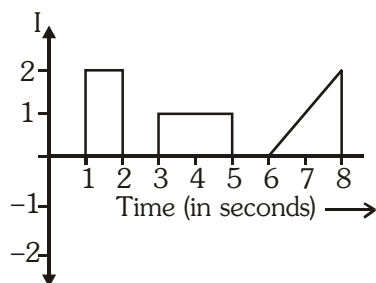


13. A wire has a non-uniform cross-section as shown in figure. A steady current flows through it. The drift speed of electrons at points P and Q is v_P and v_Q , then :-



- (1) $v_P = v_Q$ (2) $v_P < v_Q$
 (3) $v_P > v_Q$ (4) data is insufficient

14. The plot represents the flow of current through a wire for different time intervals. The ratio of charges flowing through the wire corresponding to these time intervals is (see figure) :-



- (1) 2 : 1 : 2 (2) 1 : 3 : 3
 (3) 1 : 1 : 1 (4) 2 : 3 : 4

OHM'S LAW & ELECTRICAL RESISTANCE

15. Three copper wires are there with lengths and cross-sectional areas as (ℓ, A) ; $\left(2\ell, \frac{A}{2}\right)$ and

$\left(\frac{\ell}{2}, 2A\right)$. Resistance :-

- (1) minimum for the wire of cross-sectional area $\frac{A}{2}$
 (2) minimum for the wire of cross-sectional area A
 (3) minimum for the wire of cross-sectional area 2A
 (4) same for all the three cases.

16. A wire of uniform cross-section a , length ℓ and resistance R is bent into a complete circle; the resistance between any two of diametrically opposite points will be :-

- (1) $\frac{R}{2}$ (2) $\frac{R}{4}$
 (3) $\frac{R}{8}$ (4) $4R$

17. The electric resistance of a certain wire of iron is R . If its length and radius both are doubled, then :-

- (1) the resistance will be halved and the specific resistance will remain unchanged
 (2) the resistance will be halved and the specific resistance will be doubled
 (3) the resistance and the specific resistance, will both remain unchanged
 (4) the resistance will be doubled and the specific resistance will be halved.

18. When a piece of aluminium wire of finite length is drawn to reduce its diameter to half its original value, its resistance will become :-

- (1) two times (2) four times
 (3) eight times (4) sixteen times

19. As the temperature of a metallic resistor is increased, the product of resistivity and conductivity :-

- (1) increases
 (2) decreases
 (3) may increase or decrease
 (4) remains constant.

20. If a wire is stretched, so that its length is 20% more than its initial length, the percentage increase in the resistance of the wire is :-

- (1) 40% (2) 10%
 (3) 44% (4) 25%

21. The length of a given cylindrical wire is increased by 100%. Due to the consequent decrease in diameter the change in the resistance of the wire will be :-

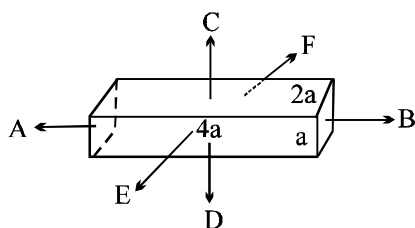
- (1) 300% (2) 200%
 (3) 100% (4) 50%

22. On increasing the temperature, the specific resistance of a conductor and a semiconductor-

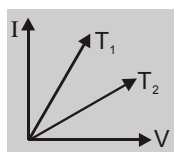
- (1) both increase
 (2) both decrease
 (3) increases and decreases respectively
 (4) decreases and increases respectively



23. A conductor with rectangular cross section has dimensions ($a \times 2a \times 4a$) as shown in figure. Resistance across AB is x , across CD is y and across EF is z . Then



- (1) $x = y = z$ (2) $x > y > z$
 (3) $y > x > z$ (4) $x > z > y$
24. Specific resistance of a conductor increases with :-
 (1) increase in temperature.
 (2) increase in cross-sectional area
 (3) increase in cross-sectional area and decrease in length.
 (4) decrease in cross-sectional area.
25. The temperature coefficient of resistance of a wire is 0.00125 per degree celcius. At 300 K its resistance is 1 ohm. The resistance of the wire will be 2 ohms at a temperature :-
 (1) 1154 K (2) 1127 K
 (3) 600 K (4) 1400 K
26. The current voltage graph for a given metallic conductor at two different temperatures T_1 and T_2 are as shown in the figure. Then :-
 (1) $T_1 > T_2$
 (2) $T_1 = T_2$
 (3) nothing can be said about T_1 and T_2
 (4) $T_1 < T_2$



27. The effective resistance is $\frac{6}{5} \Omega$, when two wires are joined in parallel. When one of the wire breaks, the effective resistance is 2 ohms. The resistance of the broken wire was :-
 (1) $\frac{3}{5} \Omega$ (2) 2Ω
 (3) $\frac{6}{5} \Omega$ (4) 3Ω

28. At what temperature will the resistance of a copper wire become three times its value at 0°C ? [Temperature coefficient of resistance for copper $= 4 \times 10^{-3}$ per $^\circ \text{C}$] :-
 (1) 400°C (2) 450°C
 (3) 500°C (4) 600°C
29. Copper and silicon are cooled from 300 K to 60 K; the specific resistance :-
 (1) decreases in copper but increases in silicon
 (2) increases in copper but decreases in silicon
 (3) increases in both
 (4) decreases in both
30. Two resistances R_1 and R_2 are made of different materials. The temperature coefficient of the material of R_1 is α and that of the material of R_2 is $-\beta$. The resistance of the series combination of R_1 and R_2 does not change with temperature, then the ratio of resistances of the two wires at 0°C will be :

- (1) $\frac{\alpha}{\beta}$ (2) $\frac{\alpha + \beta}{\alpha - \beta}$
 (3) $\frac{\alpha^2 + \beta^2}{\alpha\beta}$ (4) $\frac{\beta}{\alpha}$

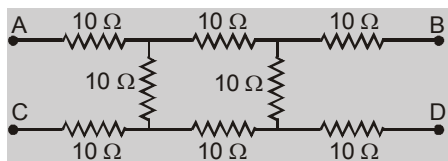
COMBINATION OF RESISTANCES & KIRCHHOFF'S LAW

31. A metal wire of resistance R is cut into three equal pieces which are then connected side by side to form a new wire, the length of which is equal to one third of the original length. The resistance of this new wire is :-
 (1) R (2) $3R$ (3) $\frac{R}{9}$ (4) $\frac{R}{3}$
32. Three resistances of values 2Ω , 3Ω and 6Ω are to be connected to yield an effective resistance of 4Ω . This can be done by connecting :
 (1) 3Ω resistance in series with a parallel combination of 2Ω and 6Ω
 (2) 6Ω resistance in series with a parallel combination of 2Ω and 3Ω
 (3) 2Ω resistance in series with a parallel combination of 3Ω and 6Ω
 (4) 2Ω resistance in parallel with a parallel combination of 3Ω and 6Ω



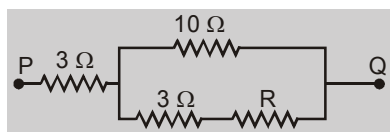
33. What will be the equivalent resistance between the points A and D ?

- (1) $10\ \Omega$
(2) $20\ \Omega$
(3) $30\ \Omega$
(4) $40\ \Omega$



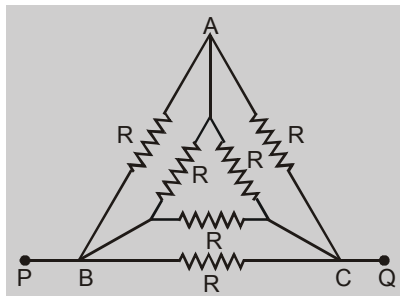
34. In the circuit shown here, what is the value of the unknown resistance R so that the total resistance of the circuit between points 'P' and 'Q' is also equal to R :-

- (1) $3\ \Omega$
(2) $\sqrt{39}\ \Omega$
(3) $\sqrt{69}\ \Omega$
(4) $10\ \Omega$

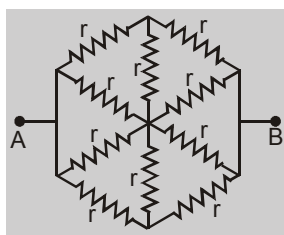


35. The resistance across P and Q in the given figure is

- (1) $\frac{R}{3}$
(2) $\frac{R}{2}$
(3) $2R$
(4) $6R$



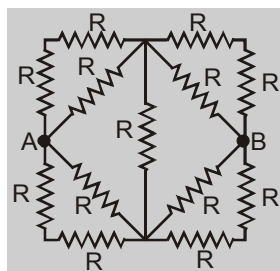
36. The resistance of the circuit between A and B is :



- (1) r (2) $0.5r$ (3) $2r$ (4) $3r$

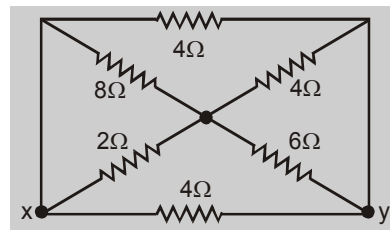
37. Thirteen resistances each of resistance $R\ \Omega$ are connected in the circuit as shown in the figure. The effective resistance between A and B is :-

- (1) $\frac{4R}{3}\ \Omega$
(2) $2R\ \Omega$
(3) $R\ \Omega$
(4) $\frac{2R}{3}\ \Omega$



38. The total resistance between x and y in ohms is :-

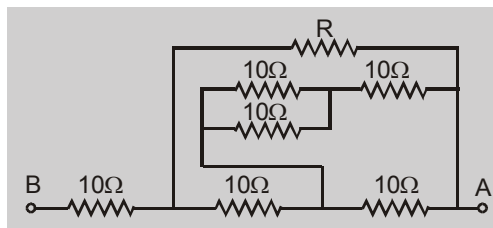
- (1) $1\ \Omega$
(2) $4\ \Omega$
(3) $\frac{4}{3}\ \Omega$
(4) $\frac{2}{3}\ \Omega$



39. The resultant resistance of n wires each of resistance r ohms is R , when they are connected in parallel. When these n resistances are connected in series, the resultant resistance will be :-

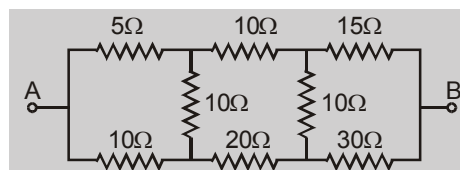
- (1) $\frac{R}{n}$ (2) $\frac{R}{n^2}$ (3) nR (4) n^2R

40. For the network of resistance shown in the fig. the equivalent resistance of the network between the points A and B is $18\ \Omega$. The value of unknown resistance R is :-



- (1) $8\ \Omega$ (2) $10\ \Omega$ (3) $16\ \Omega$ (4) $24\ \Omega$

41. In the arrangement of resistances shown below, the effective resistance between points A and B is



- (1) $20\ \Omega$ (2) $30\ \Omega$ (3) $90\ \Omega$ (4) $110\ \Omega$

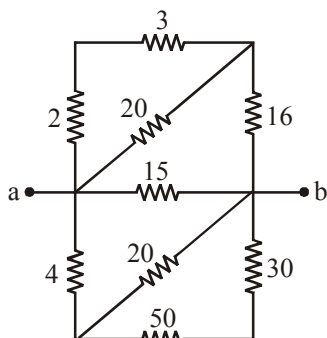
42. In the circuit shown the equivalent resistance between A and B is



- (1) R (2) $\frac{2R}{5}$
(3) $\frac{R}{3}$ (4) $2R$

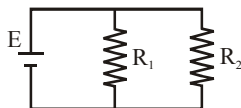


43. In the figure the numerical values denote resistances in SI units. The total resistance of the circuit between a & b will be:



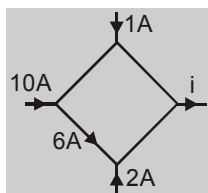
- (1) 12 ohms (2) 24 ohms.
(3) 15 ohms (4) 6 ohms

44. Resistors R_1 and R_2 have an equivalent resistance of 6 ohms when connected in the circuit shown below. The resistance of R_1 could be (in Ω) :-



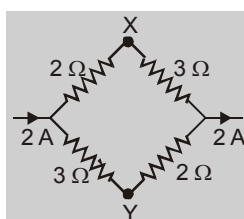
- (1) 1 (2) 5 (3) 8 (4) 4

45. Value of current i in the following circuit is :-



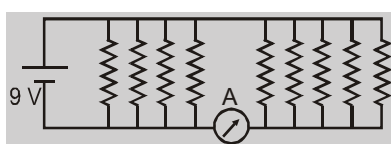
- (1) 13 A (2) 12 A
(3) 9 A (4) none of the above

46. The potential difference between X and Y in volts is :-



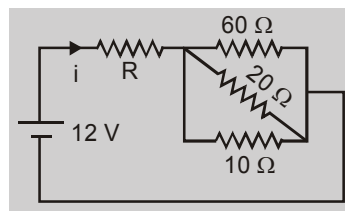
- (1) 1 (2) -1 (3) 2 (4) -2

47. If each resistance in the fig. is of 9Ω then reading of the ammeter is :-



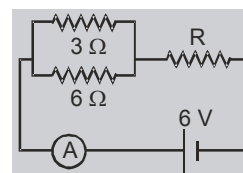
- (1) 5 A (2) 8 A (3) 2 A (4) 9 A

48. If $i = 0.25\text{ A}$ in figure, then value of R is :-



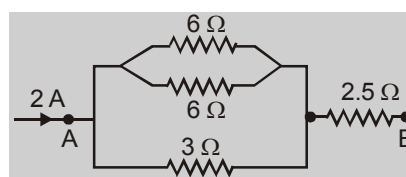
- (1) 48Ω (2) 12Ω
(3) 120Ω (4) 42Ω

49. If the ammeter in the given circuit reads 2 A, the resistance R is :-



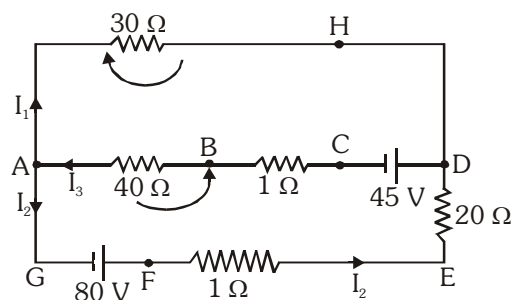
- (1) 1 ohms (2) 2 ohms
(3) 3 ohms (4) 4 ohms

50. The equivalent resistance and potential difference between A and B for the circuit are respectively :-



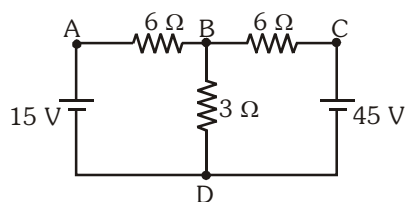
- (1) $4\Omega, 8\text{ V}$ (2) $8\Omega, 4\text{ V}$
(3) $2\Omega, 2\text{ V}$ (4) $16\Omega, 8\text{ V}$

51. For the current loops shown in the figure, Kirchhoff's loop rule for the loops AHDCBA and AHDEFGA yields these equations respectively :-



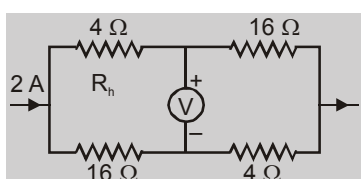
- (1) $-30 I_1 - 41 I_3 + 45 = 0$ and $-30 I_1 + 21 I_2 - 80 = 0$
(2) $30 I_1 - 41 I_3 + 45 = 0$ and $30 I_1 - 21 I_2 - 80 = 0$
(3) $30 I_1 + 41 I_3 - 45 = 0$ and $-30 I_1 + 21 I_2 + 80 = 0$
(4) $-30 I_1 - 41 I_3 - 45 = 0$ and $-30 I_1 + 21 I_2 - 80 = 0$

52. In the circuit shown in figure, find the current through the branch BD.



- (1) 1 A (2) 5 A
(3) 3 A (4) 7 A

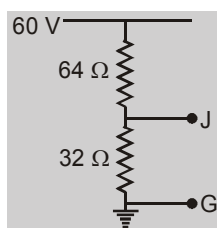
53. In the circuit shown below, the reading of the voltmeter V is :-



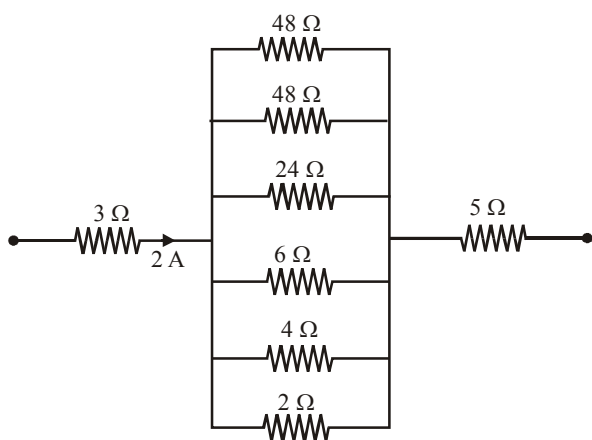
- (1) 12 V (2) 8 V
(3) 20 V (4) 16 V

54. Find the potential of J with respect of G :-

- (1) 40 V
(2) 60 V
(3) 20 V
(4) 30 V



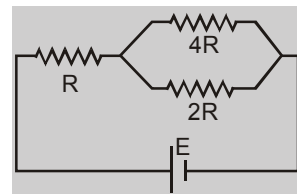
55. Find the potential difference across the 24 Ω :-



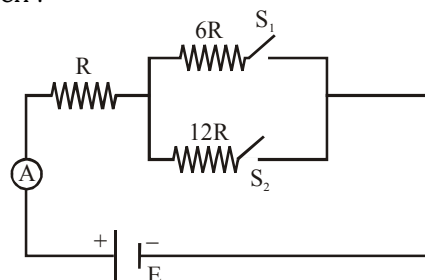
- (1) 48 volts (2) 2 volts
(3) 4 volts (4) 1 volts

56. In a network as shown in the figure the potential difference across the resistance $2R$ is (the cell has an emf E with no internal resistance) :

- (1) $2E$
(2) $\frac{4E}{7}$
(3) $\frac{E}{7}$
(4) E

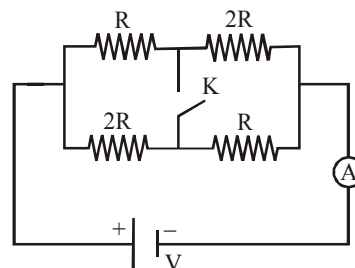


57. The reading of ammeter is I_1 when only S_1 is closed and I_2 when only S_2 is closed. The reading is I_3 when both S_1 & S_2 are closed simultaneously then :-



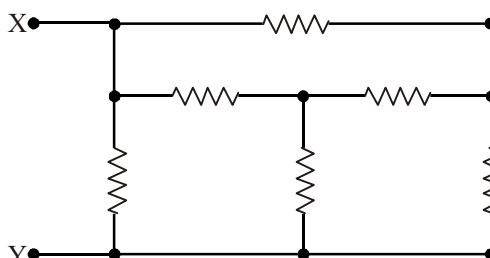
- (1) $I_1 > I_2 > I_3$ (2) $I_2 > I_3 > I_1$
(3) $I_3 > I_2 > I_1$ (4) $I_3 > I_1 > I_2$

58. How will the reading of ammeter change if the key k is closed ?



- (1) Increase
(2) Decrease
(3) Remains same
(4) Information insufficient

59. Six resistors each of 10Ω are connected as shown. The equivalent resistance between points X and Y is :

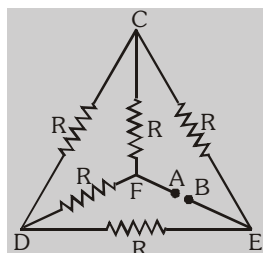


- (1) 20Ω (2) 5Ω (3) $25/3\Omega$ (4) 10Ω

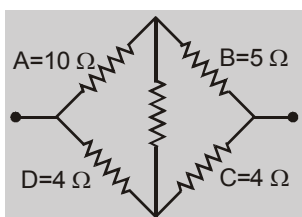


60. Five equal resistances each of resistance R are connected as shown in the Figure. A battery of voltage V is connected between A and B. The current flowing in AFCEB will be

- (1) $\frac{V}{R}$
 (2) $\frac{V}{2R}$
 (3) $\frac{2V}{R}$
 (4) $\frac{3V}{R}$

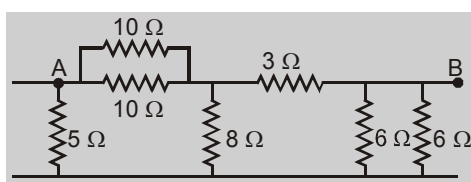


61. In a typical Wheatstone bridge the resistance in cyclic order are $A = 10 \Omega$, $B = 5 \Omega$, $C = 4 \Omega$ and $D = 4 \Omega$. For the bridge to be balanced :



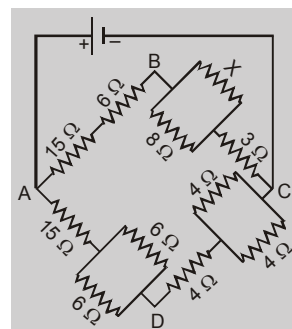
- (a) 10Ω should be connected in parallel with A
 (b) 10Ω should be connected in series with A
 (c) 5Ω should be connected in series with B
 (d) 5Ω should be connected in parallel with B
 (1) a, b (2) b, c
 (3) a, c (4) all

62. Seven resistances are connected as shown in the figure. The equivalent resistance between A and B is :-



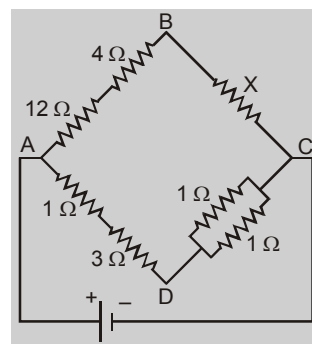
- (1) 3Ω (2) 4Ω
 (3) 4.5Ω (4) 5Ω

63. In the following circuit diagram the value of resistance X for the potential difference between B and D to be zero is :-



- (1) 4 ohms (2) 6 ohms
 (3) 8 ohms (4) 9 ohms

64. In the arrangement of resistances shown in the circuit, the potential difference between points B and D will be zero, when the unknown resistance X is :-



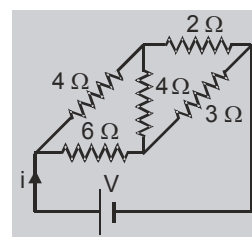
- (1) 4Ω (2) 3Ω (3) 2Ω (4) 1Ω

65. The resistance of each arm of a Wheat stone bridge is 10Ω . A resistance of 10Ω is connected in series with the galvanometer then the equivalent resistance across the battery will be :-

- (1) 10Ω (2) 15Ω (3) 20Ω (4) 40Ω

66. For the network shown in the figure the value of the current i is :-

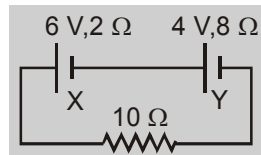
- (1) $\frac{18V}{5}$
 (2) $\frac{5V}{9}$
 (3) $\frac{9V}{35}$
 (4) $\frac{5V}{18}$



CELLS & COMBINATION OF CELLS, ELECTRIC POWER & ENERGY

67. Two cells X and Y are connected to a resistance of $10\ \Omega$ as shown in the figure. The terminal voltage of cell Y is :-

- (1) zero
- (2) 2 V
- (3) 4 V
- (4) 10 V



68. A battery has e.m.f. 4 V and internal resistance 'r'. When this battery is connected to an external resistance of 2 ohms, a current of 1 A flows in the circuit. What current will flow if the terminals of the battery are connected directly ?

- (1) 1 A
- (2) 2 A
- (3) 4 A
- (4) infinite

69. Internal resistance of primary cell depends on :-

- (1) the nature of electrolyte
- (2) the area of plates immersed in the electrolyte
- (3) the concentration of electrolyte and distance between the plates
- (4) all the above

70. The potential difference between the terminals of a cell is found to be 3 volts when it is connected to a resistance of value equal to its internal resistance. The e.m.f. of the cell is :-

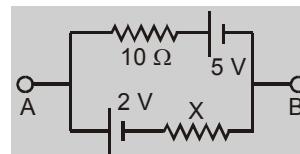
- (1) 3 V
- (2) 6 V
- (3) 1.5 V
- (4) 4.5 V

71. A current of 2 A is flowing through a cell of e.m.f. 5 V and internal resistance $0.5\ \Omega$ from negative to positive electrode. If the potential of negative electrode is 10 V, the potential of positive electrode will be :-

- (1) 5 V
- (2) 14 V
- (3) 15 V
- (4) 16 V

72. In the following circuit if $V_A - V_B = 4\text{ V}$, then the value of resistance X in ohms will be :-

- (1) 5
- (2) 10
- (3) 15
- (4) 20



73. Electromotive force of a cell is basically a

- (1) force
- (2) power
- (3) work
- (4) current capacity

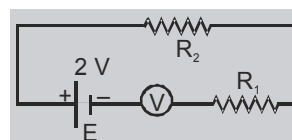
74. The terminal voltage is $\frac{E}{2}$ when a current of 2 A is flowing through $2\ \Omega$ resistance; the internal resistance of the cell is :-

- (1) $1\ \Omega$
- (2) $2\ \Omega$
- (3) $3\ \Omega$
- (4) $4\ \Omega$

75. When a resistance of 2 ohms is connected across the terminals of a cell, the current is 0.5 A. When the resistance is increased to 5 ohms, the current becomes 0.25 A. The e.m.f. of the cell is :-

- (1) 1.0 V
- (2) 1.5 V
- (3) 2.0 V
- (4) 2.5 V

76. A cell of e.m.f. 2 V and negligible internal resistance is connected to resistors R_1 and R_2 as shown in the figure. The resistance of the voltmeter, R_1 and R_2 are $80\ \Omega$, $40\ \Omega$ and $80\ \Omega$ respectively. The reading of the voltmeter is :-



- (1) 1.78 V
- (2) 1.60 V
- (3) 0.80 V
- (4) 1.33 V

77. A cell supplies a current of 0.9 A through a $2\ \Omega$ resistor and a current of 0.3 A through a $7\ \Omega$ resistor. The internal resistance of the cell is :-

- (1) $1.0\ \Omega$
- (2) $0.5\ \Omega$
- (3) $2.0\ \Omega$
- (4) $1.2\ \Omega$



- 78.** A 10 V battery with internal resistance 0.5Ω is connected across a variable resistance R . The value of R for which the power delivered to it is maximum, is equal to :-

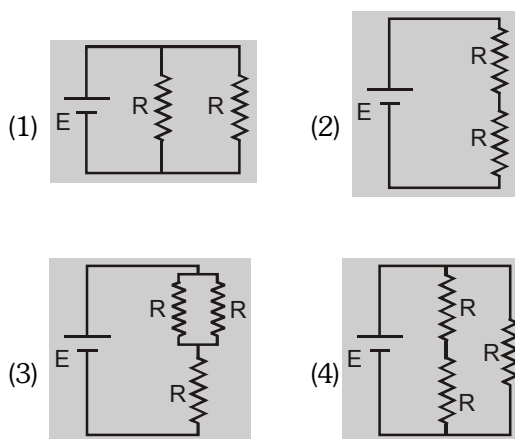
(1) 0.5Ω (2) 1Ω (3) 1.5Ω (4) 2Ω

- 79.** An electric bulb is designed to draw a power P_0 at voltage V_0 . If the voltage is V , it draws a power P , then -

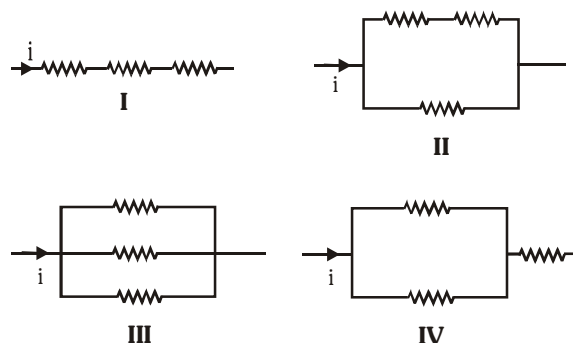
(1) $P = \left(\frac{V}{V_0}\right) P_0$ (2) $P = \left(\frac{V_0}{V}\right) P_0$

(3) $P = \left(\frac{V_0}{V}\right)^2 P_0$ (4) $P = \left(\frac{V}{V_0}\right)^2 P_0$

- 80.** Consider the four circuits shown in the figure below. In which circuit power dissipated maximum (Neglect the internal resistance of the power supply)



- 81.** Three resistances of equal value are arranged in different combinations as shown below. Arrange them in the increasing order of power dissipation :



(1) $III < II < IV < I$

(2) $II < III < IV < I$

(3) $I < IV < III < II$

(4) $I < III < II < IV$

- 82.** 25 W, 200 V and 100 W, 200 V bulbs are connected in series to a source of 400 volts. Which bulb will fuse ?

(1) 25 W

(2) 100 W

(3) Both will fuse at the same time

(4) None of the bulbs will fuse

- 83.** You are provided with 48 cells, each of emf 2 volts and internal resistance 4 ohms. What maximum current can flow in the circuit having an external resistance of 12Ω ?

(1) 1 A

(2) 1.2 A

(3) 0.96 A

(4) 1.08 A

- 84.** two electric bulbs of the same power, but with different marked voltages are connected in series across a power line . Their brightness will be :-

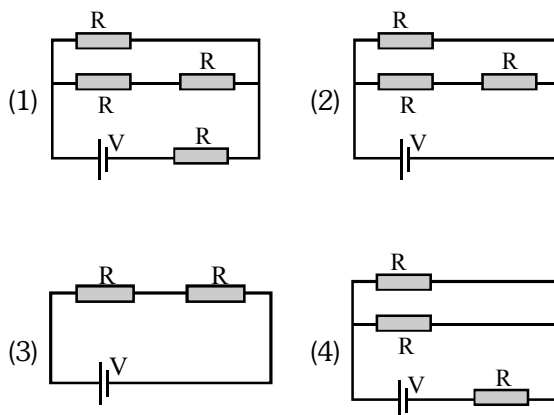
(1) directly proportional to their marked voltages

(2) inversely proportional to their marked voltages

(3) directly proportional to the squares of their marked voltages

(4) inversely proportional to the squares of their marked voltages

- 85.** Four circuits are shown below. All the batteries have the same voltage V and all resistors have the same resistance R . In which circuit does the battery delivers the most power?



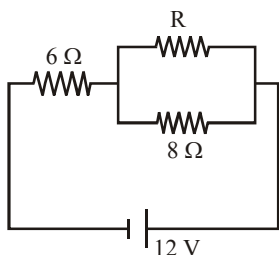
86. Four wires of the same diameter are connected, in turn, between two points maintained at a constant potential difference. Their resistivities and lengths are respectively; ρ and L (wire 1), 1.2ρ and $1.2 L$ (wire 2), 0.9ρ and $0.9 L$ (wire 3), and ρ and $1.5 L$ (wire 4). Rank the wires according to the rates at which energy is dissipated as heat, greatest first :-

- (1) $4 > 3 > 1 > 2$ (2) $4 > 2 > 1 > 3$
 (3) $1 > 2 > 3 > 4$ (4) $3 > 1 > 2 > 4$

87. Two cells, each of e.m.f. E and internal resistance r , are connected in parallel across a resistor R . The power dissipated in the resistor is maximum if :

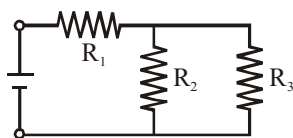
- (1) $R = r$ (2) $R = 2r$
 (3) $R = \frac{3r}{2}$ (4) $R = \frac{r}{2}$

88. In the circuit shown in figure, the power which is dissipated as heat in the 6Ω resistor is 6 W . What is the value of resistance R in the circuit ?



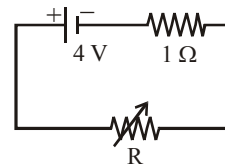
- (1) 6Ω (2) 10Ω
 (3) 13Ω (4) 24Ω

89. If power consumptions in R_1 , R_2 & R_3 are the same then what will be the relation between them ?



- (1) $R_1 = R_2 = R_3$
 (2) $R_2 = R_3 = 2R_1$
 (3) $R_2 = R_3 = 4R_1$
 (4) $R_1 = R_2 = 4R_3$

90. For different values of resistance, R power consumptions in R are given. Then which of the following values are not possible ?



- (a) 2 W (b) 5 W
 (c) 8 W (d) 4 W
 (1) Only c (2) b & c
 (3) a, b, c (4) All

MEASURING DEVICES

91. An ammeter and a voltmeter are joined in series to a cell. Their readings are A and V respectively. If a resistance is now joined in parallel with the voltmeter

- (1) both A and V will decrease
 (2) both A and V will increase
 (3) A will increase, V will decrease
 (4) A will decrease, V will increase

92. A galvanometer of 100Ω resistance yields complete deflection when 10 mA current flows. What should be the value of shunt so that it can measure currents upto 100 mA ?

- (1) 11.11Ω (2) 9.9Ω
 (3) 1.1Ω (4) 4.4Ω

93. In order to change the range of a galvanometer of $G \Omega$ resistance from V volts to nV volts what will be the value of resistance in Ω connected in series with it :-

- (1) $(n-1)G$ (2) $\frac{G}{n}$
 (3) nG (4) $\frac{G}{n-1}$

94. Resistance in the two gaps of a meter bridge are 10 ohms and 30 ohms respectively. If the resistances are interchanged, the balance point shifts by :-

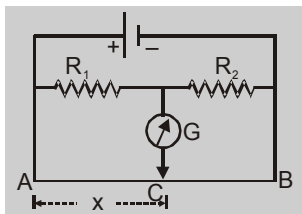
- (1) 33.3 cm (2) 66.67 cm
 (3) 25 cm (4) 50 cm



95. A galvanometer acting as a voltmeter will have :

- (1) a high resistance in series with its coil
- (2) a low resistance in parallel with its coil
- (3) a low resistance in series with its coil
- (4) a high resistance in parallel with its coil

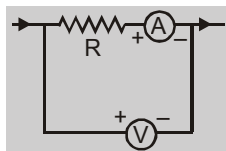
96. In the shown arrangement of the experiment of a meter bridge if AC, corresponding to null deflection of galvanometer, is x then what would be its value if the radius of the wire AB is doubled :-



- (1) x
- (2) $\frac{x}{4}$
- (3) $4x$
- (4) $2x$

97. In the following circuit, the resistance of the voltmeter is $10,000 \Omega$ and that of the ammeter is 20Ω . If the reading of the ammeter is 0.1 A and that of the voltmeter is 12 V , then the value of R is :-

- (1) 122Ω
- (2) 100Ω
- (3) 118Ω
- (4) 116Ω



98. The resistance of a galvanometer is G ohms and the range is 1 volt . The value of resistance (in Ω) used to convert it into a voltmeter of range 10 volts is :-

- (1) $9 G$
- (2) G
- (3) $\frac{1}{9} G$
- (4) $10 G$

99. A galvanometer has 36Ω resistance. If a 4Ω shunt is added to this, the fraction of current that passes through the galvanometer is :-

- (1) $\frac{1}{4}$
- (2) $\frac{1}{9}$
- (3) $\frac{1}{10}$
- (4) $\frac{1}{40}$

100. A galvanometer of resistance 100Ω gives full deflection for a current of 10^{-5} A . The value of shunt required to convert it into an ammeter of range 1 ampere , is :-

- (1) 1Ω
- (2) $10^{-3} \Omega$
- (3) $10^{-5} \Omega$
- (4) 100Ω

101. There are three voltmeters of the same range but of resistances 10000Ω , 8000Ω and 4000Ω respectively. The best voltmeter among these is the one whose resistance is :-

- (1) 10000Ω
- (2) 8000Ω
- (3) 4000Ω
- (4) all are equally good

102. 20% of the main current passes through the galvanometer. If the resistance of the galvanometer is G , then the resistance of the shunt will be :-

- (1) $\frac{G}{50}$
- (2) $\frac{G}{4}$
- (3) $50G$
- (4) $9G$

103. A voltmeter of 998 ohms resistance is connected to a cell of emf 2 volts , having internal resistance of 2 ohms . The error in measuring emf will be :-

- (1) $4 \times 10^{-1} \text{ V}$
- (2) $2 \times 10^{-3} \text{ V}$
- (3) $4 \times 10^{-3} \text{ V}$
- (4) $2 \times 10^{-1} \text{ V}$

104. An unknown resistance R_1 is connected in series with a resistance of 10Ω . This combination is connected to one gap of a metre bridge while a resistance R_2 is connected in the other gap. The balance point is at 50 cm . Now, when the 10Ω resistance is removed the balance point shifts to 40 cm . The value of R_1 is (in ohms) :-

- (1) 20
- (2) 10
- (3) 60
- (4) 40

105. A 1Ω voltmeter has a range of 1 V . Find the additional resistance which has to be joined with the series in voltmeter to increase the range of voltmeter to 100 V :-

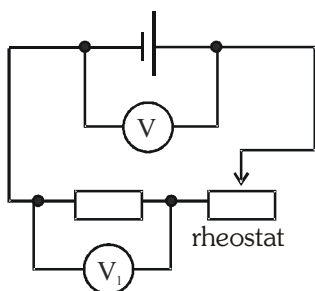
- (1) 10Ω
- (2) $\frac{1}{99} \Omega$
- (3) 99Ω
- (4) 100Ω



- 106.** A galvanometer having a resistance G and current i_a flowing in it, produces full scale deflection. If S_1 is the value of shunt which converts it into an ammeter of range $0 - i$ and S_2 is the value of the shunt for the range $0 - 2i$. Then the ratio $\frac{S_1}{S_2}$ will be :-

- (1) 1 (2) 2
(3) $\frac{1}{2} \left(\frac{i - i_a}{2i - i_a} \right)$ (4) $\left(\frac{2i - i_a}{i - i_a} \right)$

- 107.** If the rheostat slider were to move from the extreme right to the far left, How will the reading of voltmeter V_1 change?



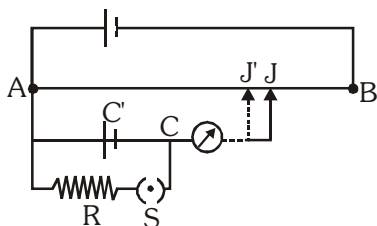
- (1) First increase and then decrease
(2) First decrease and then increase
(3) Increase continuously
(4) Decrease continuously

POTENTIOMETER

- 108.** It is observed in a potentiometer experiment that no current passes through the galvanometer, when the terminals of a cell are connected across a certain length of the potentiometer wire. On shunting the cell by a 2Ω resistance, the balancing length is reduced to half. The internal resistance of the cell is :-

- (1) 4Ω (2) 2Ω
(3) 9Ω (4) 18Ω

- 109.** In the potentiometer circuit shown in the figure, the balancing length $AJ = 60$ cm when switch S is open. When switch S is closed and the value of $R = 5 \Omega$, the balancing length $AJ' = 50$ cm. The internal resistance of the cell C' is :-



- (1) 1.2Ω (2) 1.0Ω (3) 0.8Ω (4) 0.6Ω

- 110.** In a potentiometer experiment when terminals of the cell are connected at distance of 52 cm on the wire, then no current flows through it. When 5Ω shunt resistance is connected across the cell the balancing length is 40 cm. The internal resistance of the cell (in Ω) is :-

- (1) 5 (2) $\frac{200}{52}$ (3) $\frac{52}{8}$ (4) 1.5

- 111.** A potentiometer wire has a resistance 40Ω and its length is 10 m. It is connected to a resistance of 760Ω in series. If emf of battery is 2 V then potential gradient is :-

- (1) 0.5×10^{-6} V/m (2) 1×10^{-6} V/m
(3) 1×10^{-2} V/m (4) 2×10^{-6} V/m

- 112.** A 6 volts battery is connected to the terminals of a three metres long wire of uniform thickness and 100 ohm resistance. The potential difference between two points on the wire separated by a distance of 50 cm will be :-

- (1) 3 volts (2) 1 volt
(3) 1.5 volts (4) 2 volts

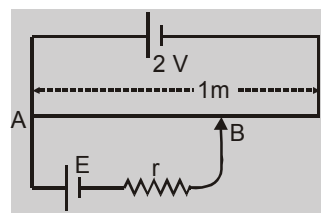
- 113.** Potentiometer is used for measuring :

- (1) potential difference (2) current
(3) internal resistance (4) All of these

- 114.** Length of a potentiometer wire is kept long and uniform to achieve :-

- (1) uniform and more potential gradient
(2) non-uniform and more potential gradient
(3) uniform and less potential gradient
(4) non-uniform and less potential gradient

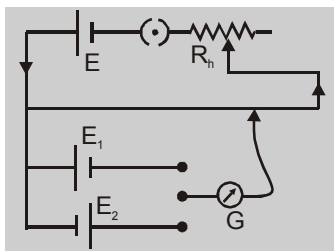
- 115.** In figure battery E is balanced over a 55 cm length of potentiometer wire but when a resistance of 10Ω is connected in parallel with the battery then it balances over a 50 cm length of the potentiometer wire then internal resistance r of the battery is :-



- (1) 1Ω (2) 3Ω (3) 10Ω (4) 5Ω

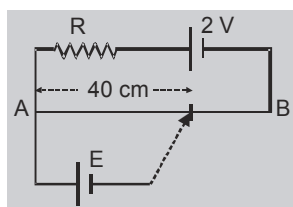


- 116.** The following diagram shows the circuit for the comparison of e.m.f. of two cells. The circuit can be corrected by :-



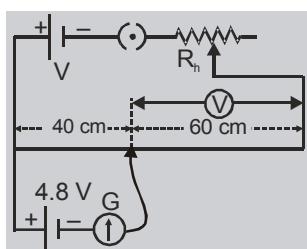
- (1) reversing the terminals of E
- (2) reversing the terminals of E_1
- (3) reversing the terminals of E_2
- (4) reversing the current in R_h .

- 117.** AB is a potentiometer wire of length 100 cm and resistance 10 ohms. It is connected in series with a resistance $R = 40$ ohms and a battery of e.m.f. 2 V and negligible internal resistance. If a source of unknown e.m.f. E is balanced by 40 cm length of the potentiometer wire, the value of E is :-



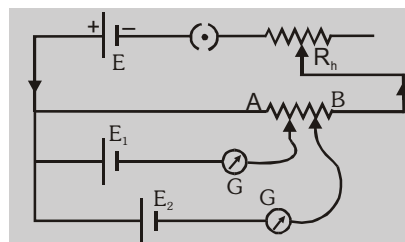
- (1) 0.8 V
- (2) 1.6 V
- (3) 0.08 V
- (4) 0.16 V

- 118.** In the following circuit, the reading of the voltmeter will be :- (in volts)



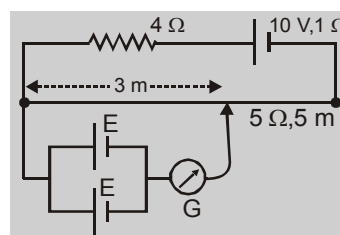
- (1) 7.2
- (2) 4.8
- (3) 6
- (4) 4

- 119.** In the following diagram, the deflection in the galvanometer in a potentiometer circuit is zero, then :-



- (1) $E_1 > E_2$
- (2) $E_2 > E_1$
- (3) $E_1 = E_2$
- (4) $E_1 + E_2 = E$

- 120.** A resistance of 4Ω and a wire of length 5 m and resistance 5Ω are joined in series and connected to a cell of e.m.f. 10 V and internal resistance 1Ω . A Parallel combination of two identical cells is balanced across 300 cm length of the wire. The e.m.f. E of each cell is :



- (1) 1.5 V
- (2) 3.0 V
- (3) 0.67 V
- (4) 1.33 V

- 121.** The emf of a standard cell is balanced over a 150 cm length of a potentiometer wire. When this cell is shunted by a 2Ω resistance, the null point is obtained at 100 cm. The value of internal resistance of the cell is :-

- (1) 0.1 ohms
- (2) 1 ohms
- (3) 2 ohms
- (4) 0.5 ohms

- 122.** The sensitivity of a potentiometer is increased by
- (1) increasing the emf of the cell.
 - (2) increasing the length of the potentiometer wire
 - (3) decreasing the length of the potentiometer wire
 - (4) none of the above.

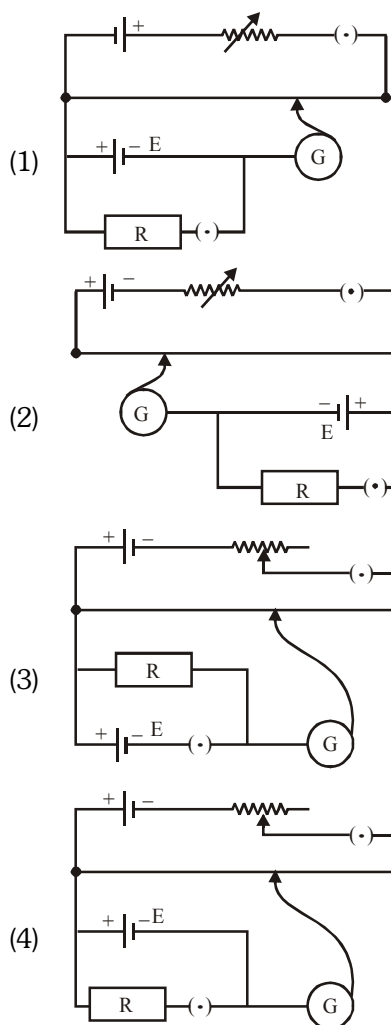
123. A potential gradient is established in the wire by a standard cell for the comparison of emf's of two cells in a potentiometer experiment. Which possibility of the following will lead to the failure of the experiment ?

- (1) the emf of the standard cell is higher than that of the other cells.
- (2) the diameter of the wire is equal along its length
- (3) the number of wires is ten.
- (4) the emf of the standard cell is less than that of either cells

124. Potentiometer wire length is 10 m, having a total resistance of $10\ \Omega$. If a battery of emf 2 volts (of negligible internal resistance) and a rheostat are connected to it then the potential gradient is $20\ \text{mV/m}$; find the resistance imparted through the rheostat :-

- (1) $90\ \Omega$
- (2) $990\ \Omega$
- (3) $40\ \Omega$
- (4) $190\ \Omega$

125. The correct circuit for the determination of internal resistance of a battery by using potentiometer is :



EXERCISE-I (Conceptual Questions)

ANSWER KEY

Que.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Ans.	2	2	2	3	2	2	3	4	2	2	3	4	3	3	3
Que.	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Ans.	2	1	4	4	3	1	3	4	1	2	4	4	3	1	4
Que.	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Ans.	3	3	3	3	1	2	4	3	4	3	1	1	4	3	1
Que.	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
Ans.	1	1	4	1	1	4	2	1	3	2	2	4	1	2	2
Que.	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75
Ans.	3	2	3	3	1	4	1	2	4	2	2	4	3	2	2
Que.	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
Ans.	3	2	1	4	1	1	1	1	3	2	4	4	4	3	2
Que.	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105
Ans.	3	1	1	4	1	1	2	1	3	2	1	2	3	1	3
Que.	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120
Ans.	4	3	2	2	4	3	2	4	3	1	3	4	1	2	2
Que.	121	122	123	124	125										
Ans.	2	2	4	1	4										



Directions for Assertion & Reason questions

These questions consist of two statements each, printed as Assertion and Reason. While answering these Questions you are required to choose any one of the following four responses.

- (A) If both Assertion & Reason are True & the Reason is a correct explanation of the Assertion.
 (B) If both Assertion & Reason are True but Reason is not a correct explanation of the Assertion.
 (C) If Assertion is True but the Reason is False.
 (D) If both Assertion & Reason are false.

1. **Assertion :** Electric field inside a current carrying wire is zero.
Reason : Net charge in a current carrying wire is non zero.
 (1) A (2) B (3) C (4) D
2. **Assertion :** A voltmeter must be connected in parallel in a circuit and it should have a high resistance.
Reason : The voltmeter in the circuit must not affect the potential difference measured by it.
 (1) A (2) B (3) C (4) D
3. **Assertion :** Electric field due to steady current carrying wire is zero outside the wire.
Reason : Net charge present in a current carrying wire is zero.
 (1) A (2) B (3) C (4) D
4. **Assertion :** Kirchhoff's voltage law indicates that electrostatic field is conservative.
Reason : Potential difference between two points in a circuit does not depend on path.
 (1) A (2) B (3) C (4) D
5. **Assertion :** Terminal potential difference of a cell is always less than its emf.
Reason : Potential drop due to internal resistance of cell increases the terminal potential difference.
 (1) A (2) B (3) C (4) D
6. **Assertion :** When wheatstone bridge is balanced, the current through the cell depends on the resistance of galvanometer.
Reason : In the balanced condition, current through the galvanometer is very high.
 (1) A (2) B (3) C (4) D
7. **Assertion :** Potentiometer measures the correct value of emf of a cell.
Reason : No current flows through the cell being balanced at the null point of potentiometer.
 (1) A (2) B (3) C (4) D
8. **Assertion :** When identical cells are connected in parallel to an external load, the effective e.m.f. increases.
Reason : All the cells will be sending unequal currents to the external load in the same direction.
 (1) A (2) B (3) C (4) D
9. **Assertion :** Potentiometer is an ideal instrument to measure the potential difference.
Reason : Potential gradient along the potentiometer wire can be made very small.
 (1) A (2) B (3) C (4) D
10. **Assertion :** Current is a scalar quantity.
Reason : Electric current arises due to continuous flow of charged particles or ions.
 (1) A (2) B (3) C (4) D
11. **Assertion :-** Total current entering a circuit is equal to that leaving it by Kirchhoff's law. [AIIMS 2013]
Reason :- It is based on conservation of energy.
 (1) A (2) B (3) C (4) D
12. **Assertion :-** When a straight wire is bent to form L-shape, its resistance increases.
Reason :- Electrons take longer time to travel along a bent wire as compared to travel along a straight wire.
 (1) A (2) B (3) C (4) D
13. **Assertion :-** In a metallic conductor, current is due to the drift of free electrons in a definite direction.
Reason :- A current carrying conductor is negatively charged.
 (1) A (2) B (3) C (4) D
14. **Assertion :-** Electric field is present in the vicinity of a current carrying wire.
Reason :- The principle of conservation of charge is not obeyed, when charges are in motion.
 (1) A (2) B (3) C (4) D



15. **Assertion :-** As temperature of a metallic current carrying the wire is increased, its resistance increases.

Reason :- Decrease in temperature results in a decrease of electric field strength along the conductor so that the current reduces.

(1) A (2) B (3) C (4) D

16. **Assertion :-** Conductivity of a metals is much higher than that of an electrolyte at room temperature.

Reason :- Free electron density in metals is much larger than the density of ions in electrolytes and also free electrons have greater mobility than ions.

(1) A (2) B (3) C (4) D

17. **Assertion :-** A domestic electric appliance working on a three pin, will continue working if the thick pin is removed.

Reason :- The thick pin is used only as a safety device.

(1) A (2) B (3) C (4) D

18. **Assertion :-** The value of temperature coefficient of resistance is positive for metals.

Reason :- The value of temperature coefficient of resistance is negative for insulators.

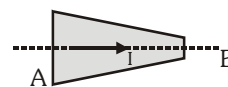
(1) A (2) B (3) C (4) D

19. **Assertion :-** Two unequal resistances are connected in parallel across a cell, then current through the smaller resistance is more.

Reason :- In a parallel combination the potential difference will be the same.

(1) A (2) B (3) C (4) D

20. **Assertion :-** Consider a current carrying wire whose cross sectional area decreases gradually along the direction of current, as shown in figure. As one goes from cross-section A to cross-section B, the drift speed of electrons increases.



Reason :- Electric field intensity at any cross-section in a current carrying wire is inversely proportional to its cross sectional area.

(1) A (2) B (3) C (4) D

21. **Assertion :-** EMF of battery decreases with time. [AIIMS-2016]

Reason :- Internal resistance increases with time.

(1) A (2) B (3) C (4) D

22. **Assertion :-** When we use new battery, it can give voltage near to its EMF. [AIIMS-2016]

Reason :- The Internal Resistance of new cell is very low.

(1) A (2) B (3) C (4) D

23. **Assertion :-** Resistivity of metals decreases with decrease in temperature but have some finite value as the temperature approaches absolute zero.

Reason :- The residual resistivity near absolute zero is caused primarily by the collision of electrons with impurities and imperfections in the metal.

[AIIMS-2017]

(1) A (2) B (3) C (4) D

24. **Assertion :-** Discharge currents are very large.

Reason :- Atmospheric conductivity is low.

(1) A (2) B (3) C (4) D

EXERCISE-II (Assertion & Reason)

ANSWER KEY

Que.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Ans.	4	1	1	1	4	4	1	4	2	2	3	4	3	4	3
Que.	16	17	18	19	20	21	22	23	24						
Ans.	1	1	2	1	2	2	1	1	2						

